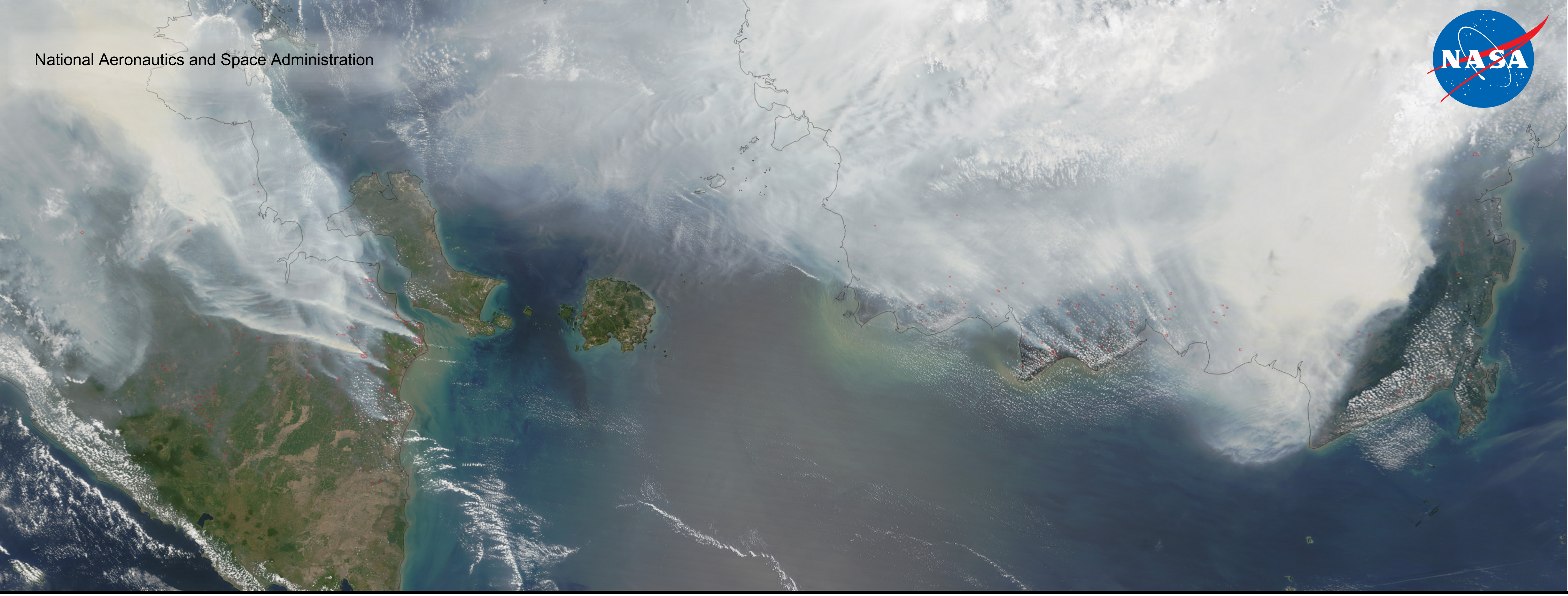
National Aeronautics and Space Administration



Remote Sensing of Trace Gases

Melanie Follette-Cook, Pawan Gupta, and Bryan Duncan

NASA Remote Sensing for Air Quality Applications, March 20-23, 2018, Jakarta, Indonesia

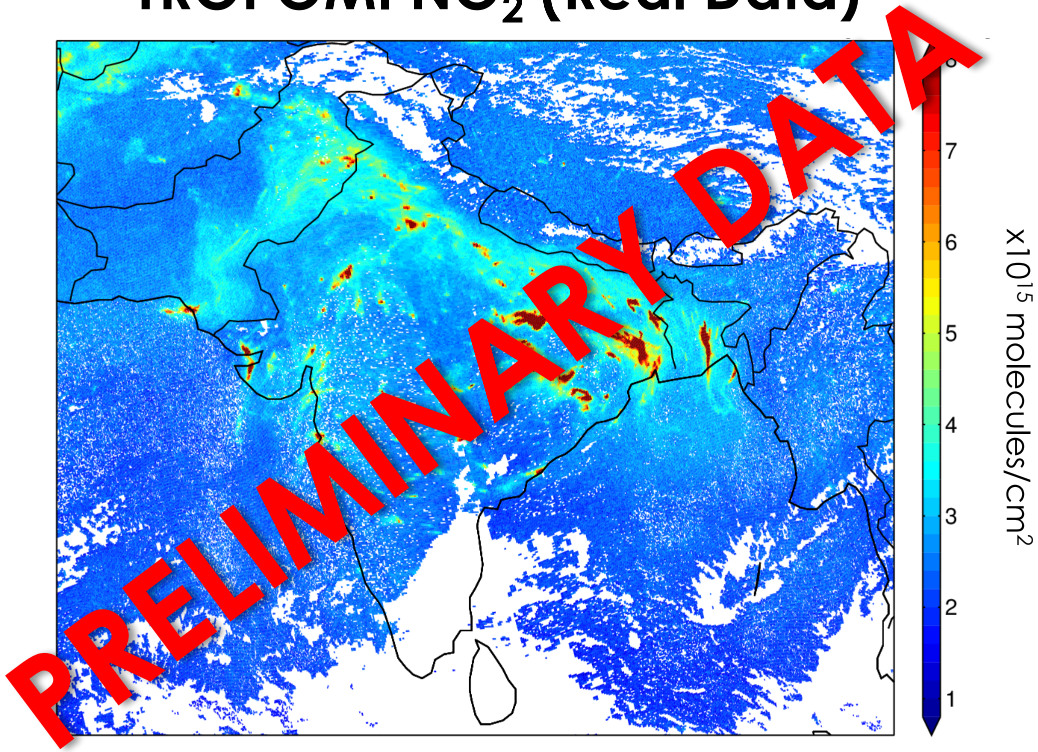
Satellite Remote Sensing of Trace Gases for Air Quality

Overview

- **This presentation will cover several trace gases relevant to air quality**
  - O_3, HCHO, NO_2, SO_2, and CO
- Some fundamentals of observing trace gases
- Information on specific data products
  - Limitations & strengths for air quality
- Specific examples of how data are used

November 28, 2017

TROPOMI NO_2 (Real Data)

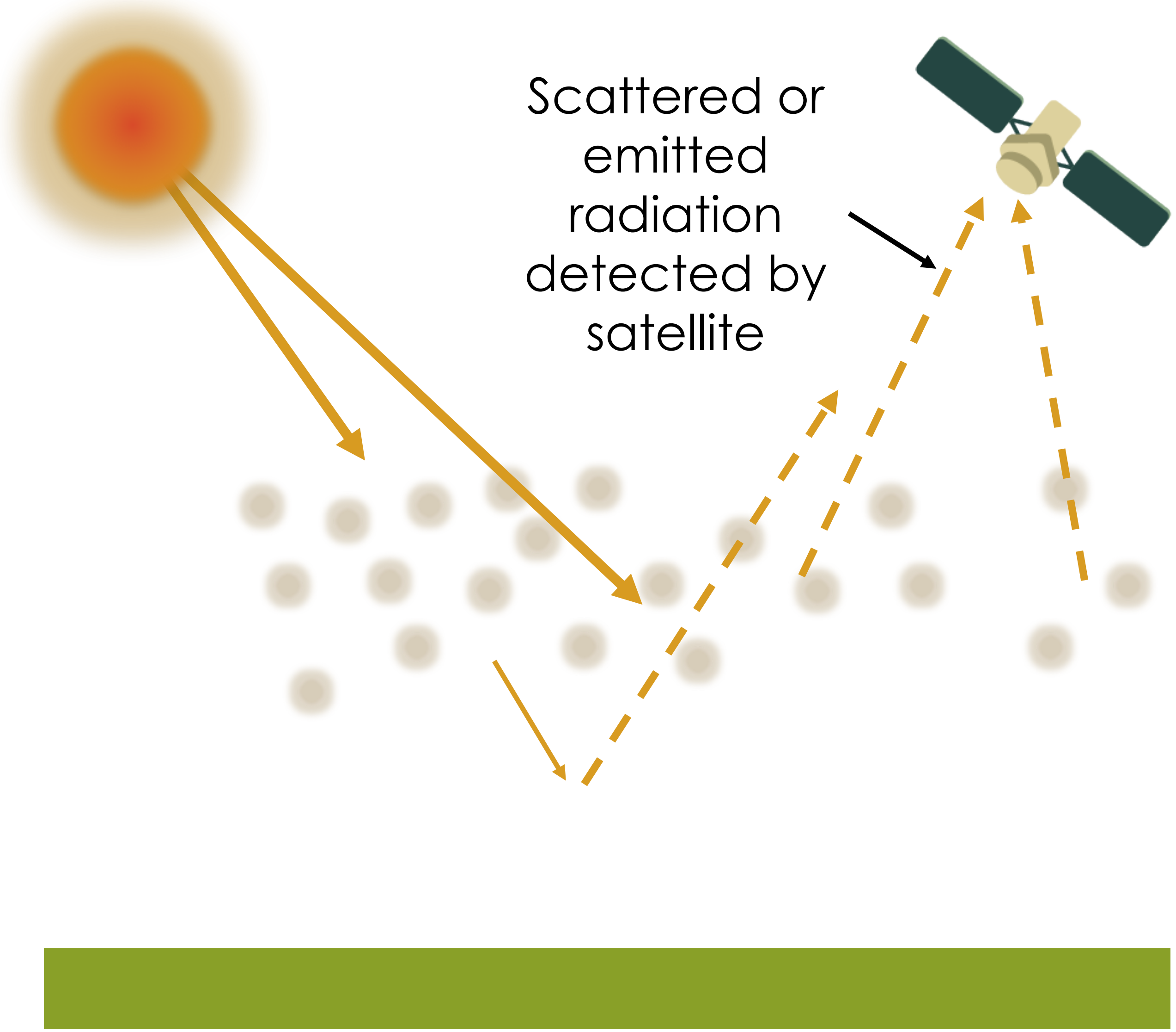


Spatial Resolution = 3.5 x 7.0 km^2

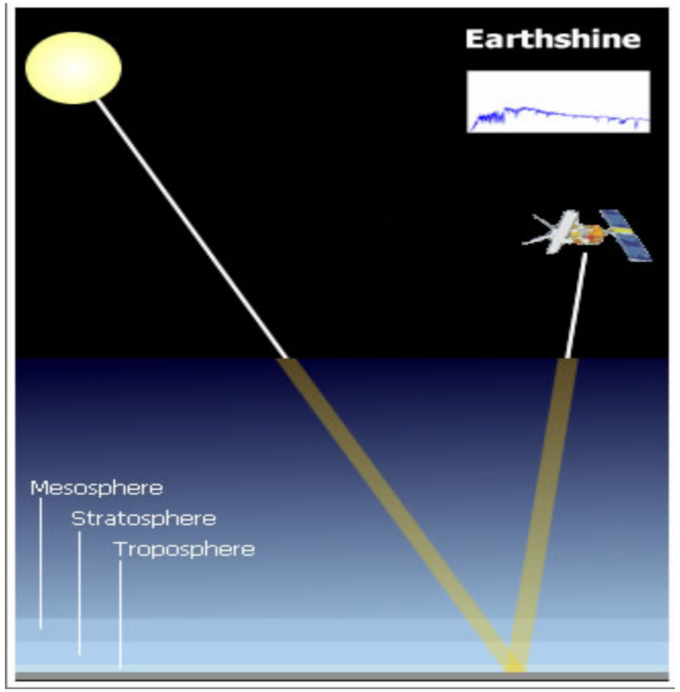
TROPOMI data courtesy of ESA

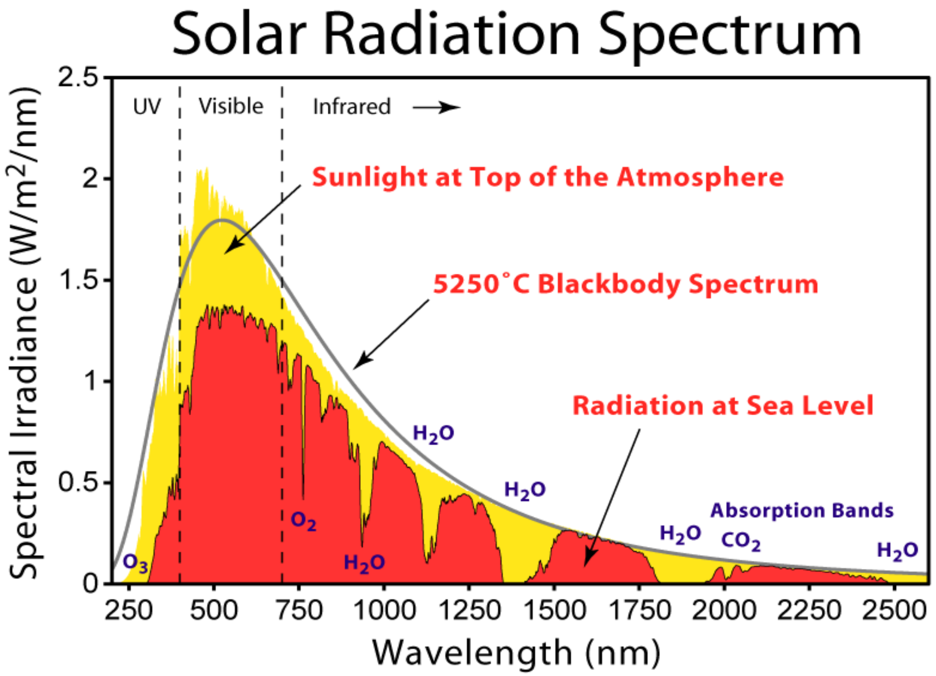
Measuring Trace Gases from Space

- Satellites detect backscattered UV, visible, and/or emitted thermal radiation
- We know the distinct absorption spectra of each trace gas
- We can identify a "spectral fingerprint" for each atmospheric constituent
- Retrieval algorithms (a model) infer physical quantities such as number density, partial pressure, and column amount



How Satellites Measure Trace Gases





- Trace gases use the signature of gas absorption
- All satellite remote sensing measurements of the troposphere are based on the use of electromagnetic radiation and its interaction with constituents in the atmosphere

Image Credit (Right): [Wikipedia, Solar Spectrum]

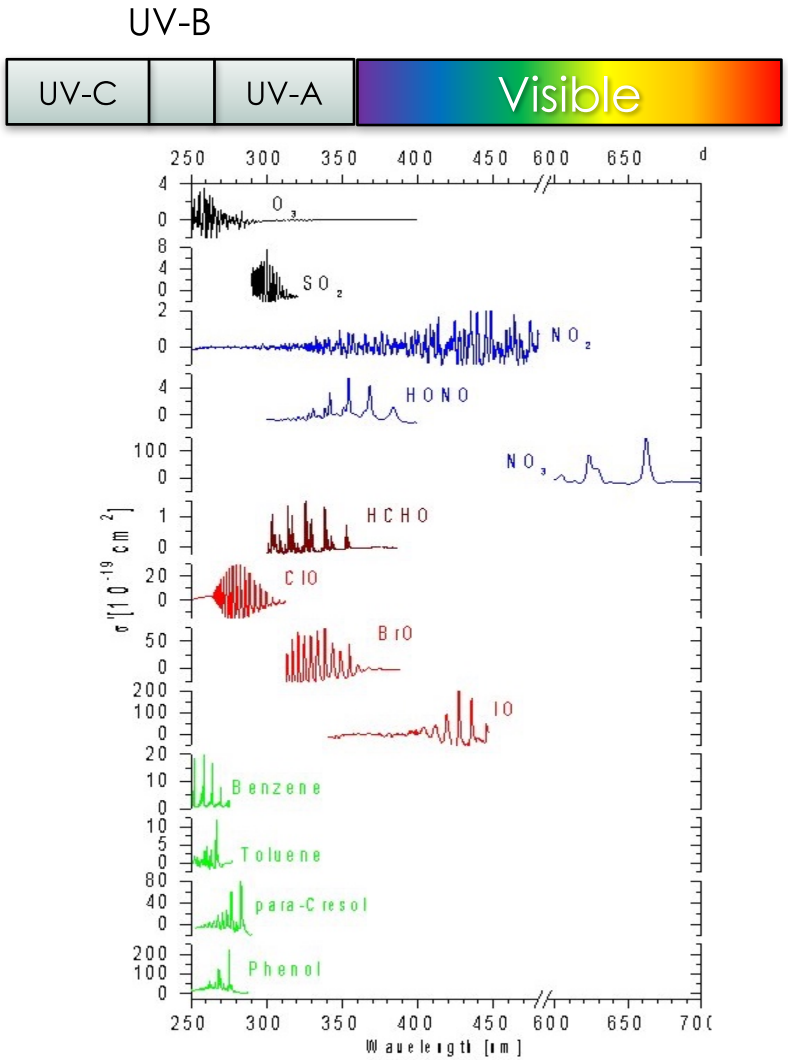
A Spectral Signature of a Trace Gas is Unique like a Fingerprint

vs

- One fingerprint on a drink can allows the owner to be identified
- If a lot of people touch the drink can, it can be very difficult to identify any one person. This is the case for trace gases as spectral signatures often overlap.

Image Credits (left to right): Walmart Canada; Wikimedia Commons, The Photographer

A Spectral Signature of a Trace Gas is Unique like a Fingerprint

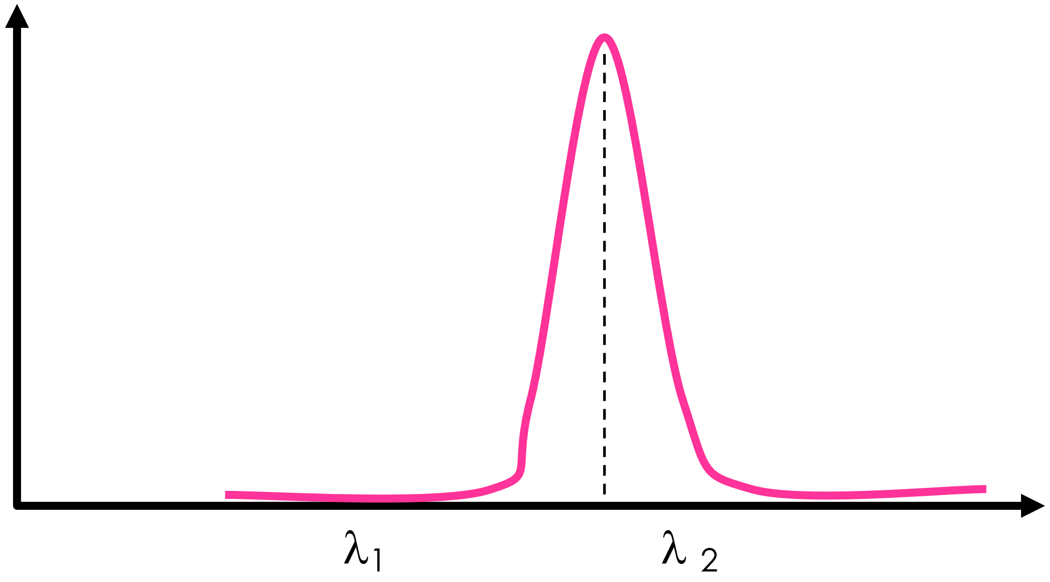


σ_λ = absorption cross-section of a trace gas as a function of wavelength (λ)

That is, σ_λ is the ability of a molecule to absorb a photon of a particular wavelength

A Spectral Signature of a Trace Gas is Unique Like a Fingerprint

- Two wavelengths (λ) are used in retrievals
  - λ_1 is NOT absorbed by trace gas
  - λ_2 is absorbed by trace gas



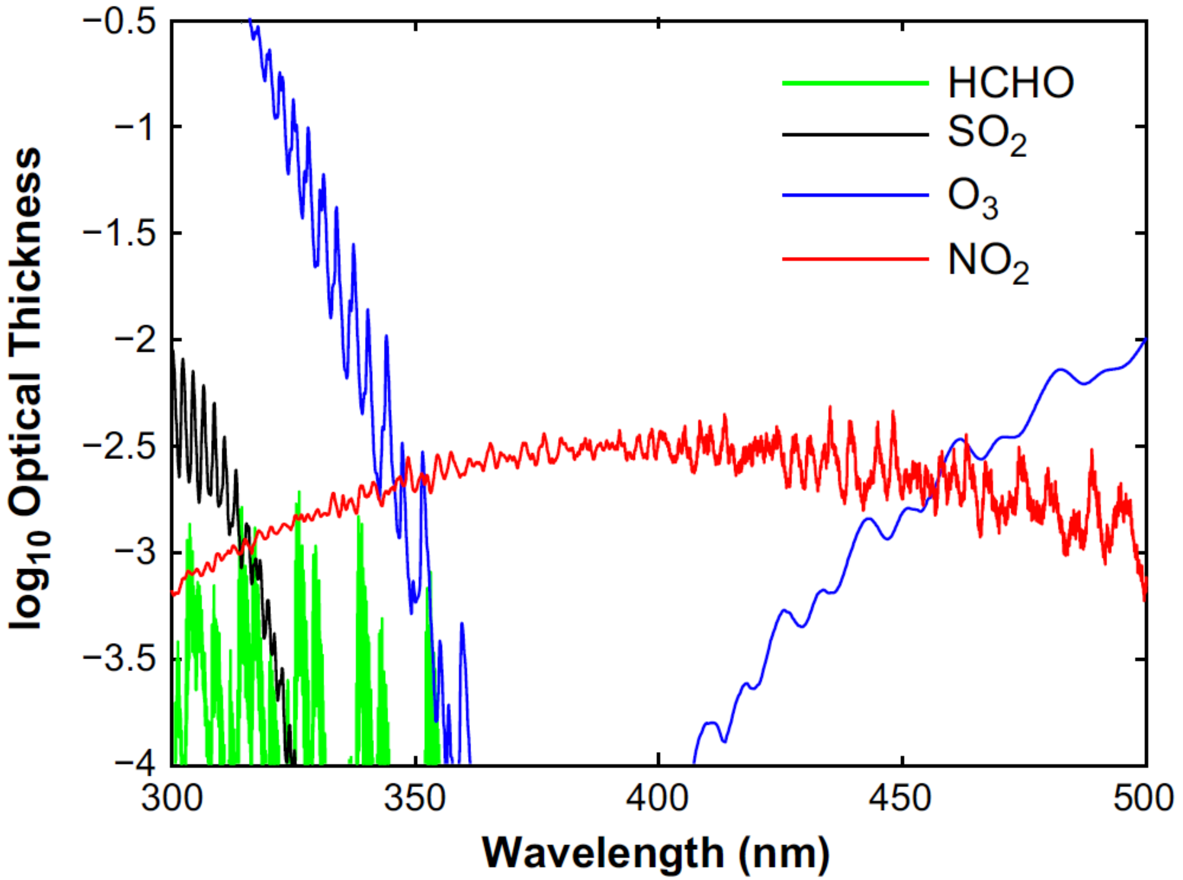
Optical Depth = Cross Section * Trace Gas Abundance

Optical depth or thickness (τ_λ) is a measure of the extinction of the solar beam by trace gases. In other words, trace gases in the atmosphere can block sunlight by absorbing or by scattering light

$$\tau_\lambda = \sigma_\lambda \, \Omega_v$$

where Ω_v is the trace gas abundance over the atmospheric path length, such as a vertical column

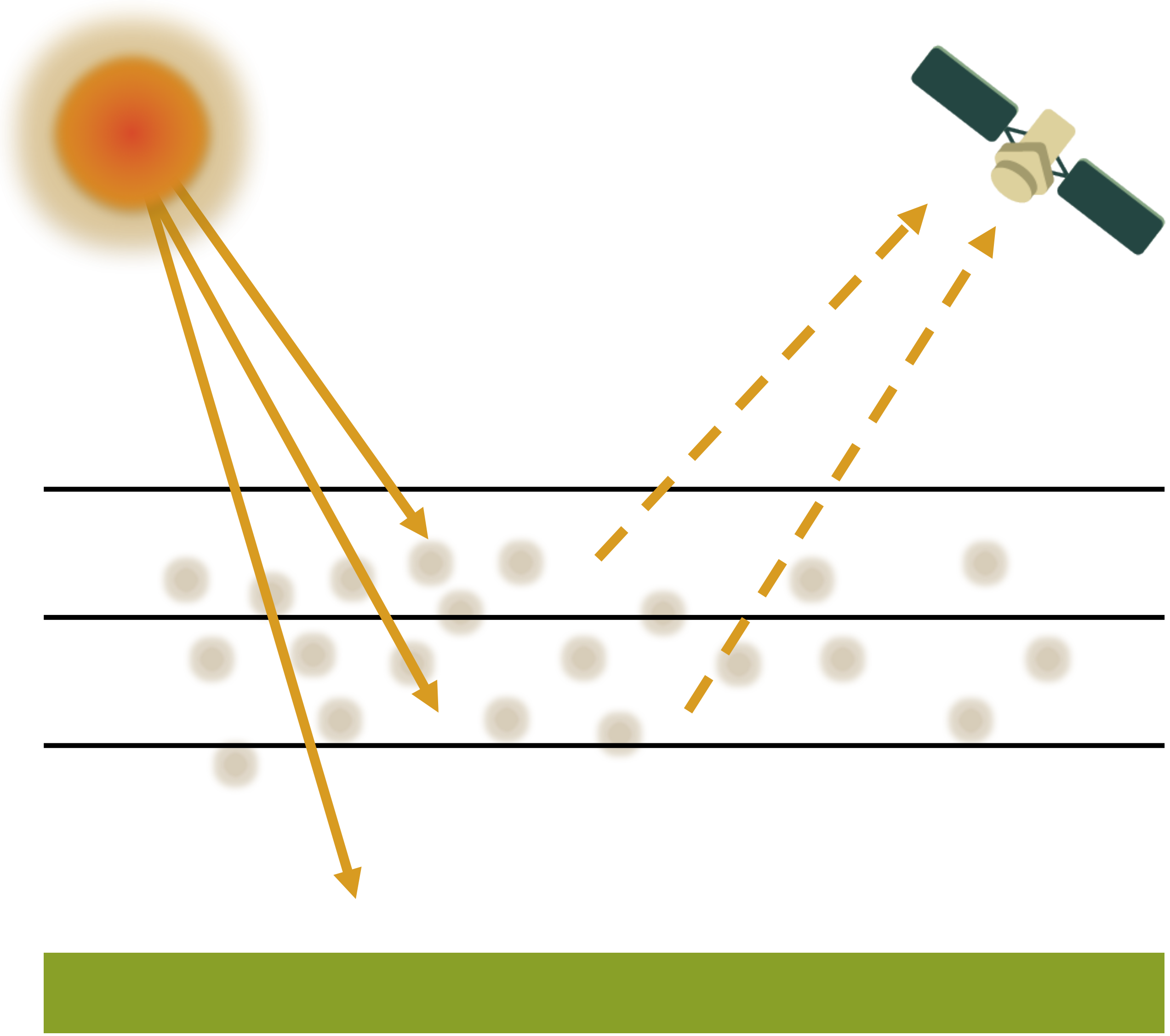
Note: optical depth is calculated in different ways for trace gases and aerosols



Martin, R.V., Satellite remote sensing of surface air quality, *Atmos. Environ.*, 42, 7823-7843, 2008.

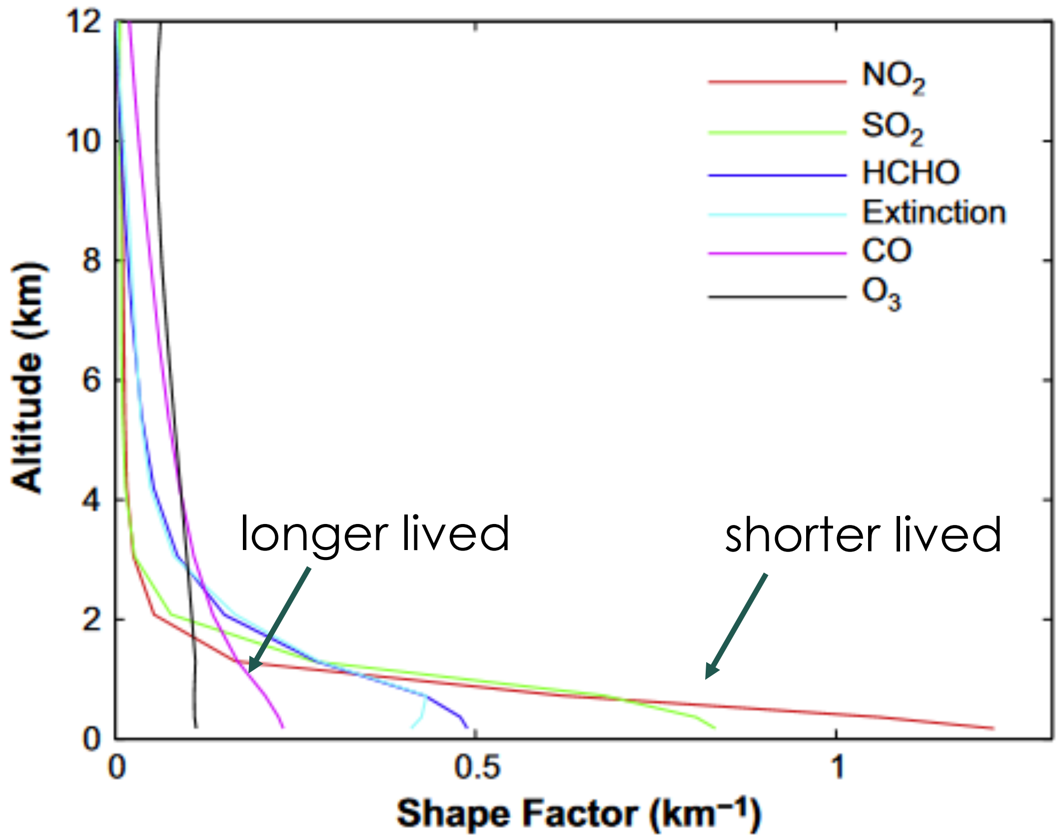
Vertical Distribution

- Very little information can be obtained on the vertical distribution of trace gases in the troposphere from a nadir view
- For some trace gases, like ozone, measurements techniques using different wavelengths (e.g., combining UV, visible, and IR measurements) can provide some vertical information
  - The penetration depth of photons increases with increasing wavelengths
  - Example: volcanic plumes of SO_2



Vertical Distribution

- Some information on vertical distribution can be inferred by taking the altitude of the trace gas source and its lifetime into account
- (Right) Normalized vertical profiles as calculated with a global chemical transport model (GEOS-Chem)
  - Trace gases profiles are the number density divided by the tropospheric column (units = 1/km)
  - Normalized aerosol extinction is calculated by dividing by aerosol optical depth
  - All profiles integrate to unity over the troposphere



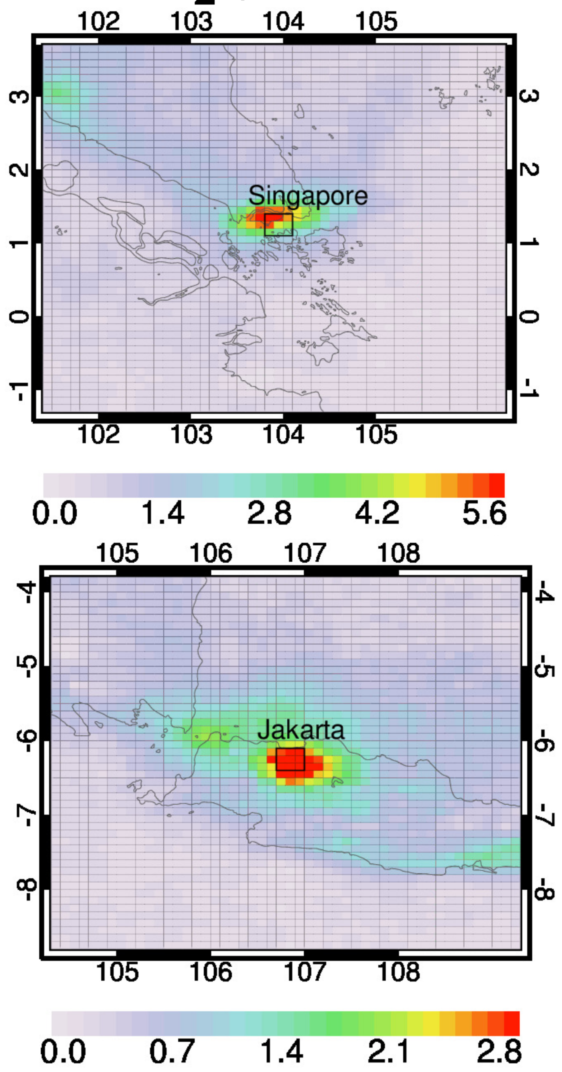
Martin, R.V., Satellite remote sensing of surface air quality, Atmos. Environ., 42, 7823-7843, 2008.

Vertical Distribution

- Some information on vertical distribution can be inferred by taking the altitude of the trace gas source and its lifetime into account
- Examples:
  – NO_2 is short-lived and primarily emitted from fossil fuel combustion (e.g., cars, power plants), so most NO_2 is found near the surface
  – SO_2 is similar to NO_2 for man-made sources (e.g., power plants), but it can be high in the atmosphere when volcanoes are the source

https://airquality.gsfc.nasa.gov

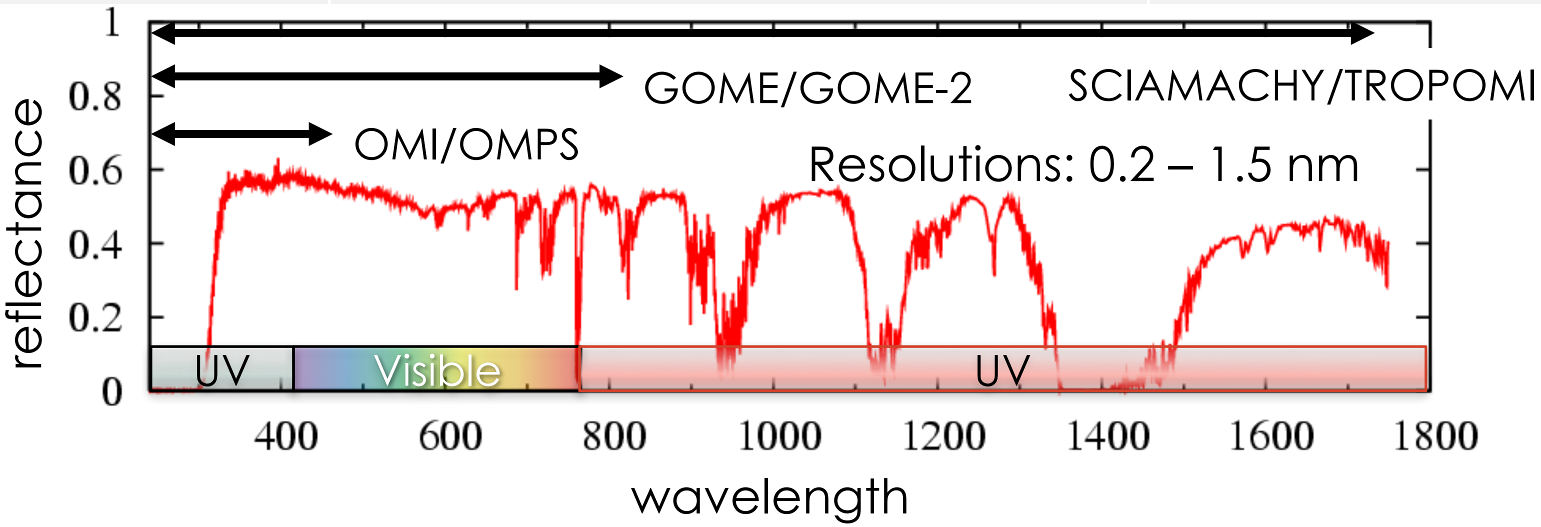
OMI NO_2 ($\times 10^{15}$ molec/cm^2)



Hyperspectral Instruments

Current and Past Satellite UV-Visible Spectrometers

Instrument	Satellite	Wavelength
GOME (defunct)	ERS-2	240 – 800 nm
SCIAMACHY (defunct)	Envisat	240 – 1750 nm
OMI	EOS-Aura	270 – 500 nm
GOME-2	Metop-A	240 – 800 nm
OMPS	Suomi-NPP	250 – 400 nm
TROPOMI	Sentinel-5P	270 – 775 nm, 2305 – 2385 nm



Data Formats & Resolutions

Data Level	Description
Level 0	Raw data at full instrument resolution
Level 1A	Raw data that have been time-referenced and supplemented with information such as radiometric and geometric calibration coefficients and geo-referencing parameters. These are computed and appended, but not applied to Level 0 data.
Level 1B	Level 1A data that has been processed to sensor units (not all instruments have Level 1B source data)
Level 2	Derived geophysical variables at the same resolution and location as Level 1 source data
Level 2G & 3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency
Level 4	Model output or results from analyses of lower level data (e.g. variables derived from multiple measurements)

Trace Gases: Using Level 3 vs. Level 2 Data

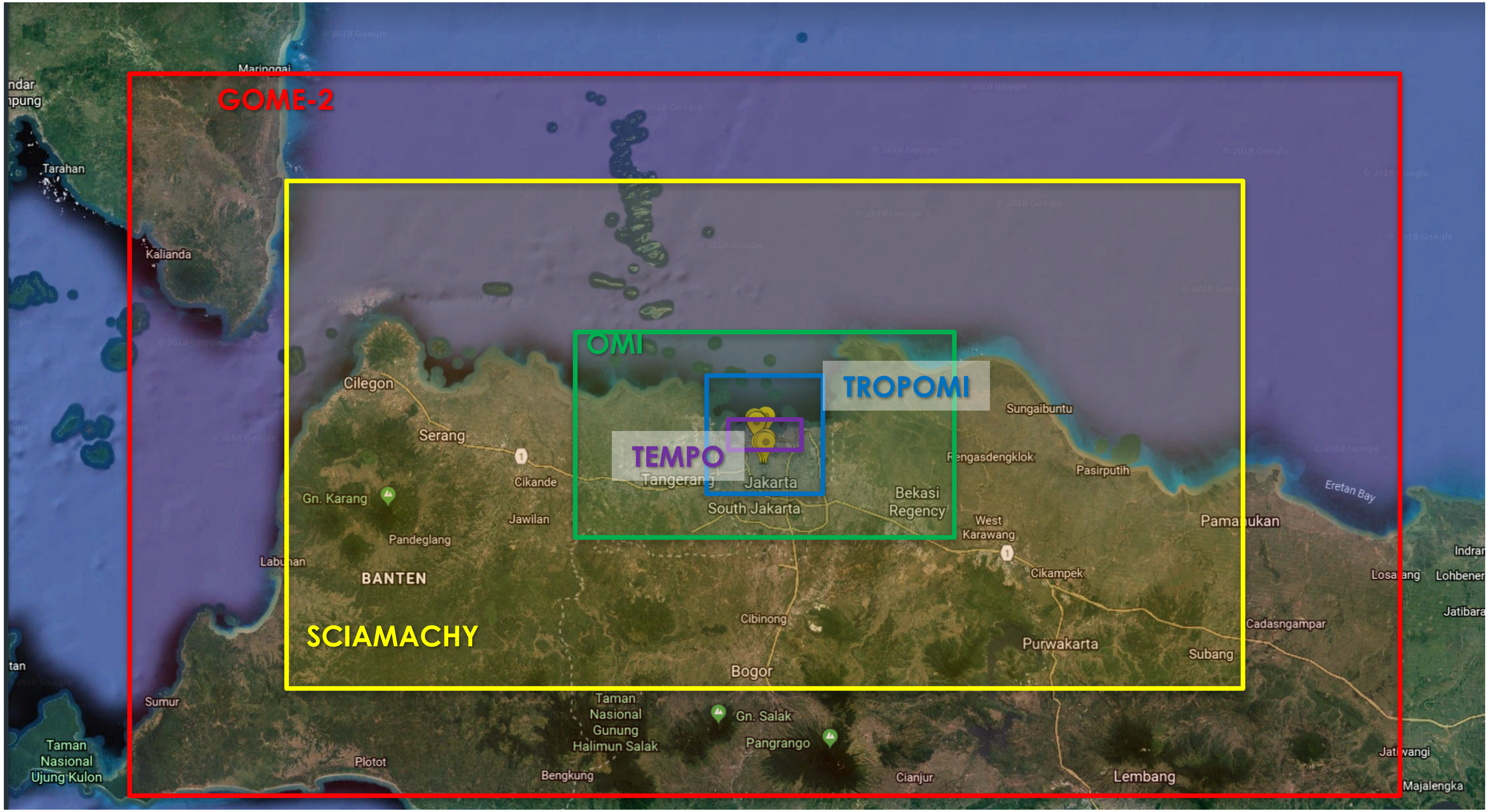
- Advantages
  - Uniform grid
  - One file per day
  - Smaller sized files
  - Quality flags and filtering criteria have been applied
- Limitations
  - Typically at coarser resolution than L2
  - L2 observation typically at the same location as the L1 source data

Spatial Resolution: Trace Gases

- Spatial resolution of current satellite instruments (10s to <10 km diameter)
  - good enough to map tropospheric concentration fields on local to regional scales
  - fine enough to resolve individual power plants and large cities
- For species with short atmospheric lifetimes (e.g. NO_2), averaging over larger satellite pixels can lead to significant dilution of signals from point sources, complicating quantitative analysis and separation of emission sources
- For quantitative analysis: Level 2 and high resolution gridded Level 3 data are optimal

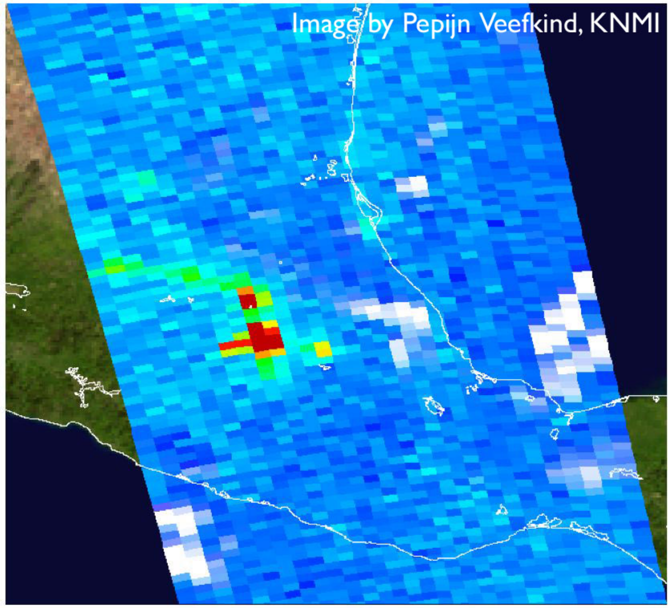
Source: Richter, 20

Evolution of Spatial Resolution

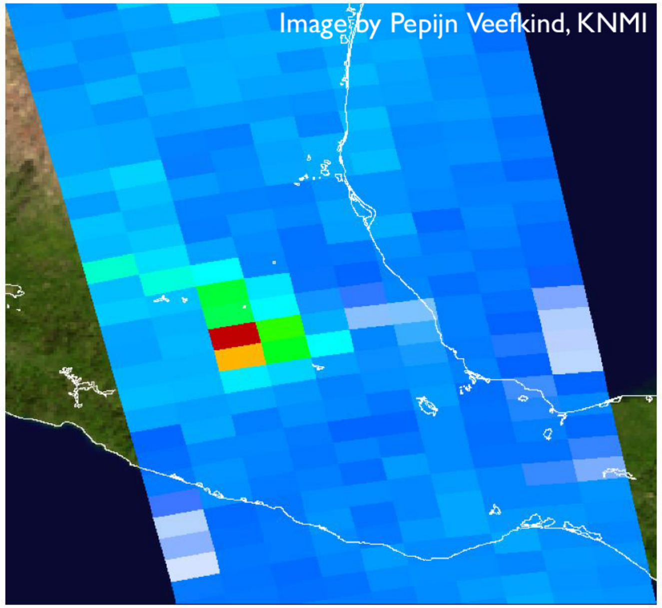


Perspective…

Spatial Resolution



OMI 24x13 km^2



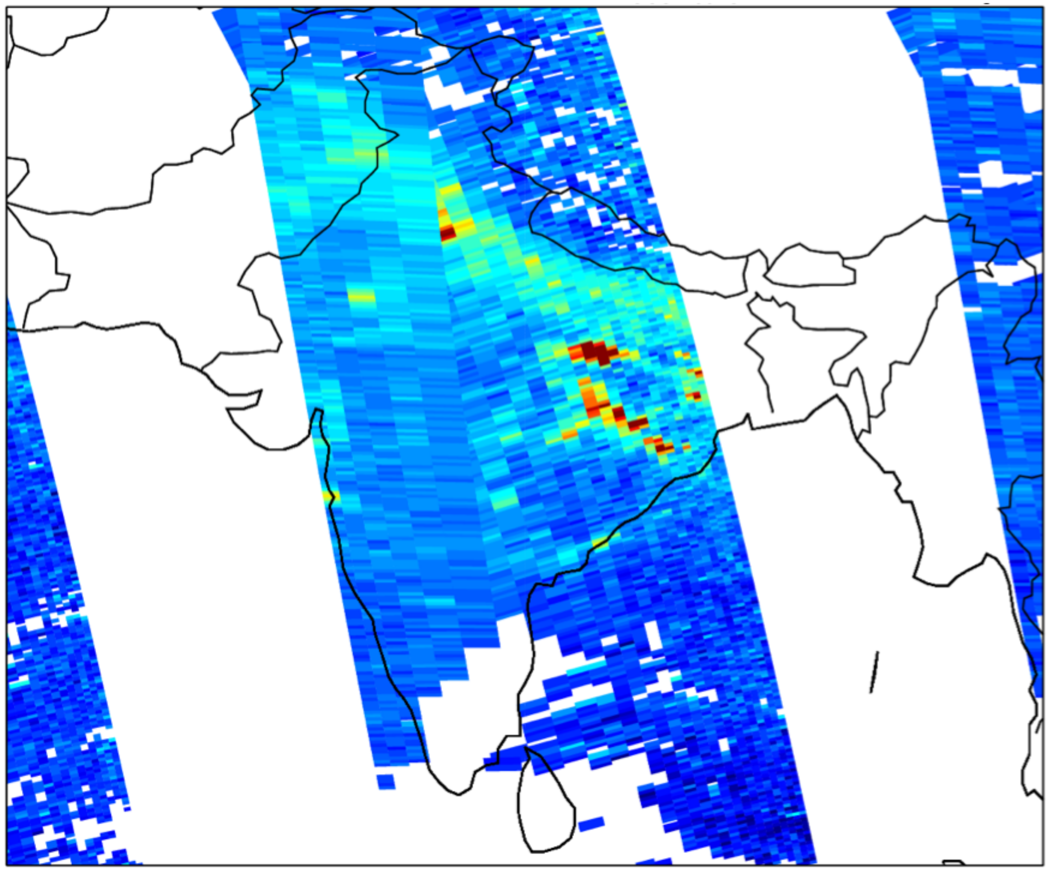
Approx. GOME-2 72x39 km^2

Mexico City, Jan. 20, 2005

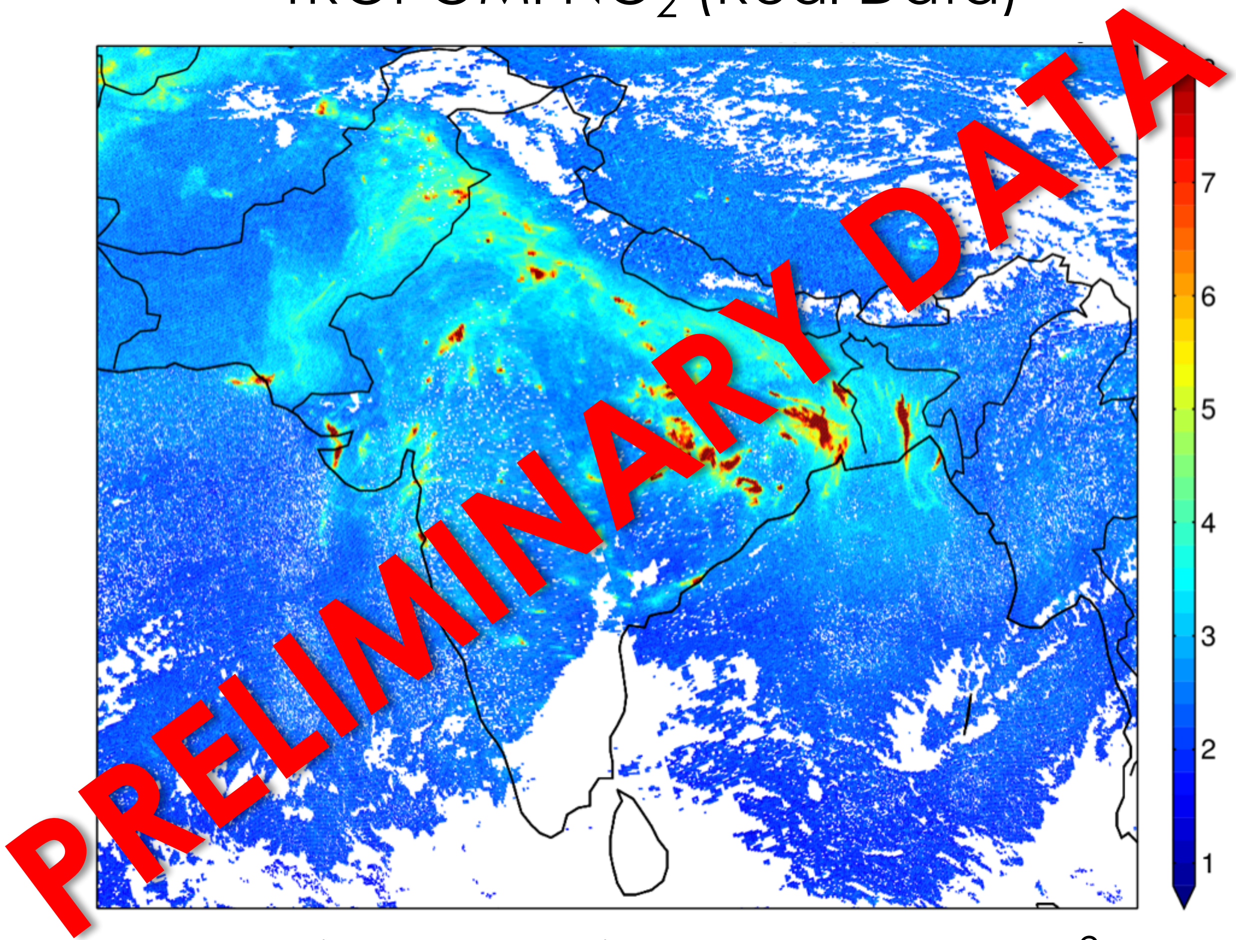
TROPOMI: Impact of Resolution

November 28, 2017

OMI NO_2 (Real Data)



TROPOMI NO_2 (Real Data)



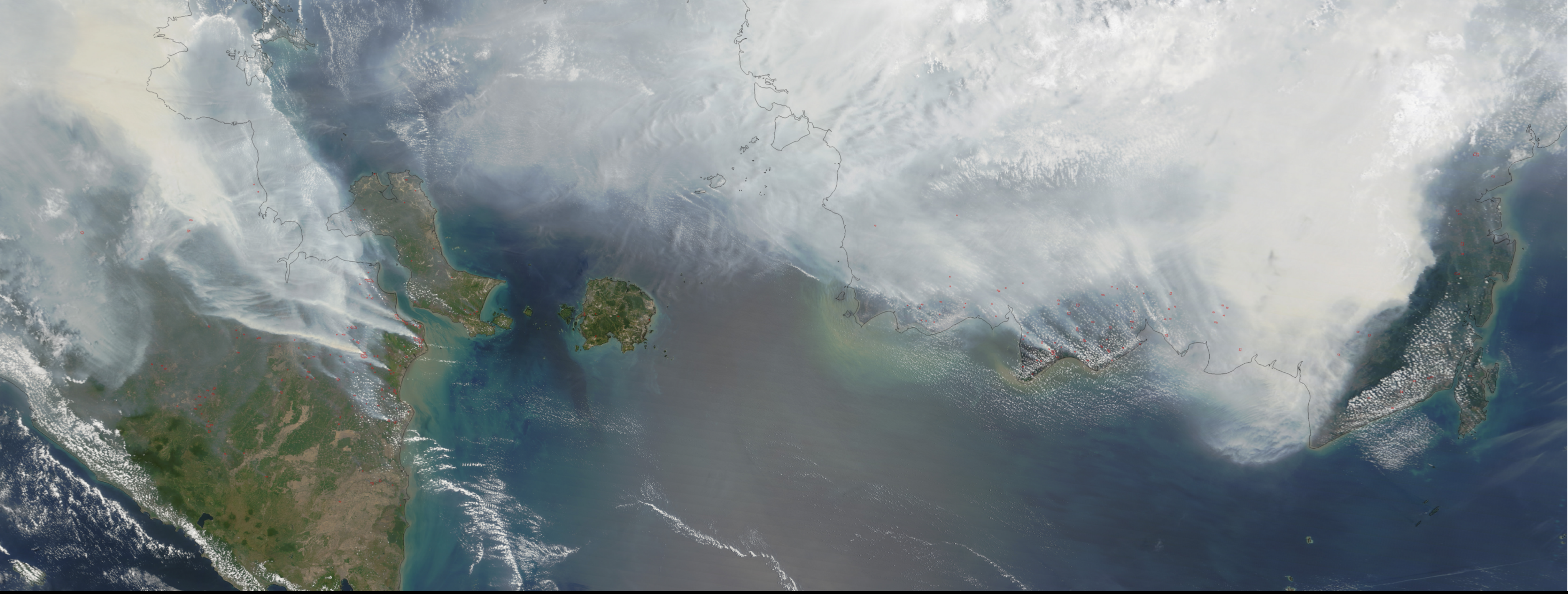
Spatial Resolution = 3.5 x 7.0 km^2

TROPOMI data courtesy of ESA

Quantification of Gas Abundances - Units

Satellite Tracer	Units
TROPOMI, OMI O_3, SO_2	Dobson Units (DU)
TROPOMI, OMI NO_2, Column Amounts (also AIRS and MOPITT CO)	Molecules/cm^2
AIRS and MOPITT CO Vertical Levels	Volume Mixing Ratio (ppmv, ppbv, pptv)

1 DU = 2.69×10^{16} molec/cm^2
ppm = 1 molec in 10^6 (or one part per million)
ppb = 1 molec in 10^9
ppt = 1 molec in 10^{12}



OMI

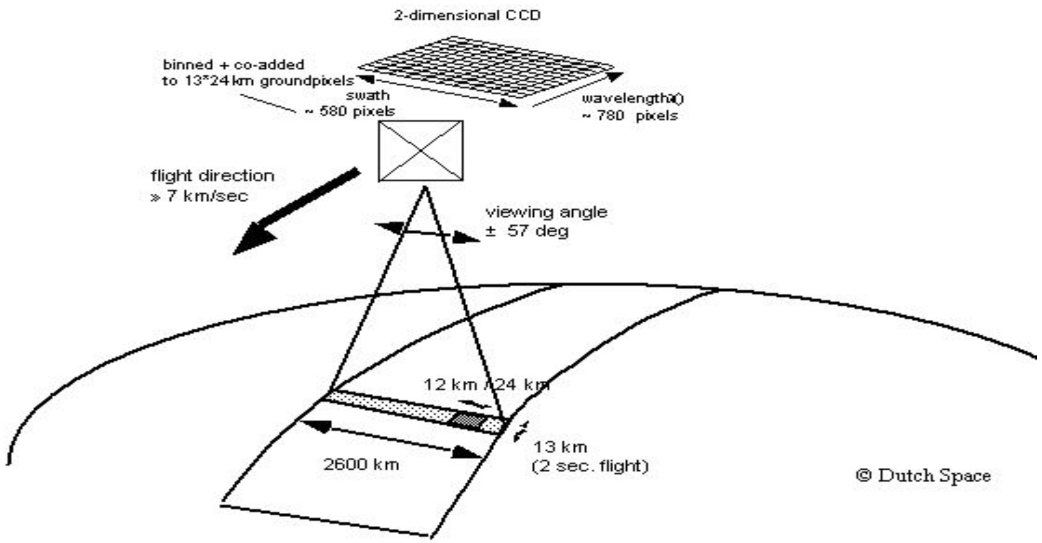
Ozone Monitoring Instrument (OMI)

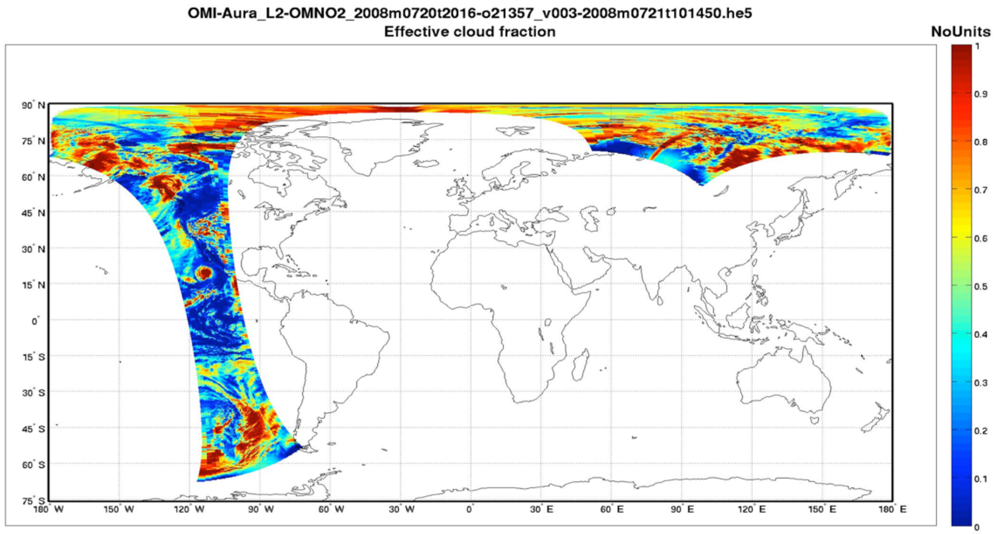
- Launched July 15, 2004
- NASA EOS Aura Satellite
- Nadir-viewing UV/Visible
  - 270 – 310 nm at 0.6 nm
  - 310 – 500 nm at 0.45 nm
- 1:45 p.m. equatorial crossing time
- 13x24 km^2 at nadir
- Daily global coverage

- Products
  - Total Column O_3
  - Tropospheric Column O_3
  - Aerosol optical depth (in UV)
  - Column Formaldehyde
  - Column NO_2
  - Tropospheric column NO_2
  - Column SO_2

Data Granule

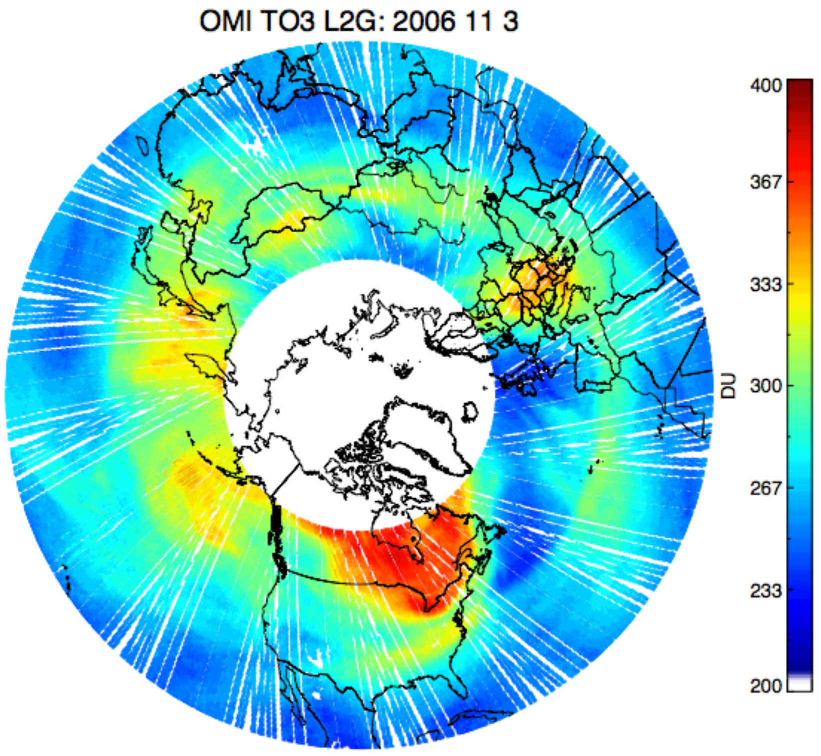
- Product File
  - covers sunlit portion of the orbit with an approx. 2,600 km wide swath
  - contains 60 binned pixels or scenes per viewing line
- 14 or 15 granules are produced daily, providing fully contiguous coverage of the globe

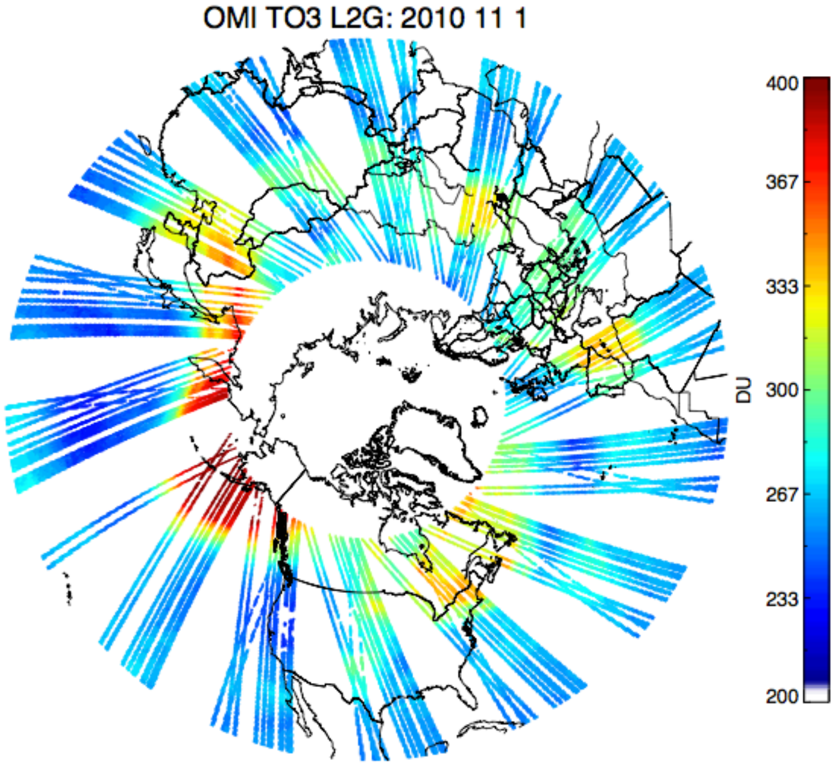


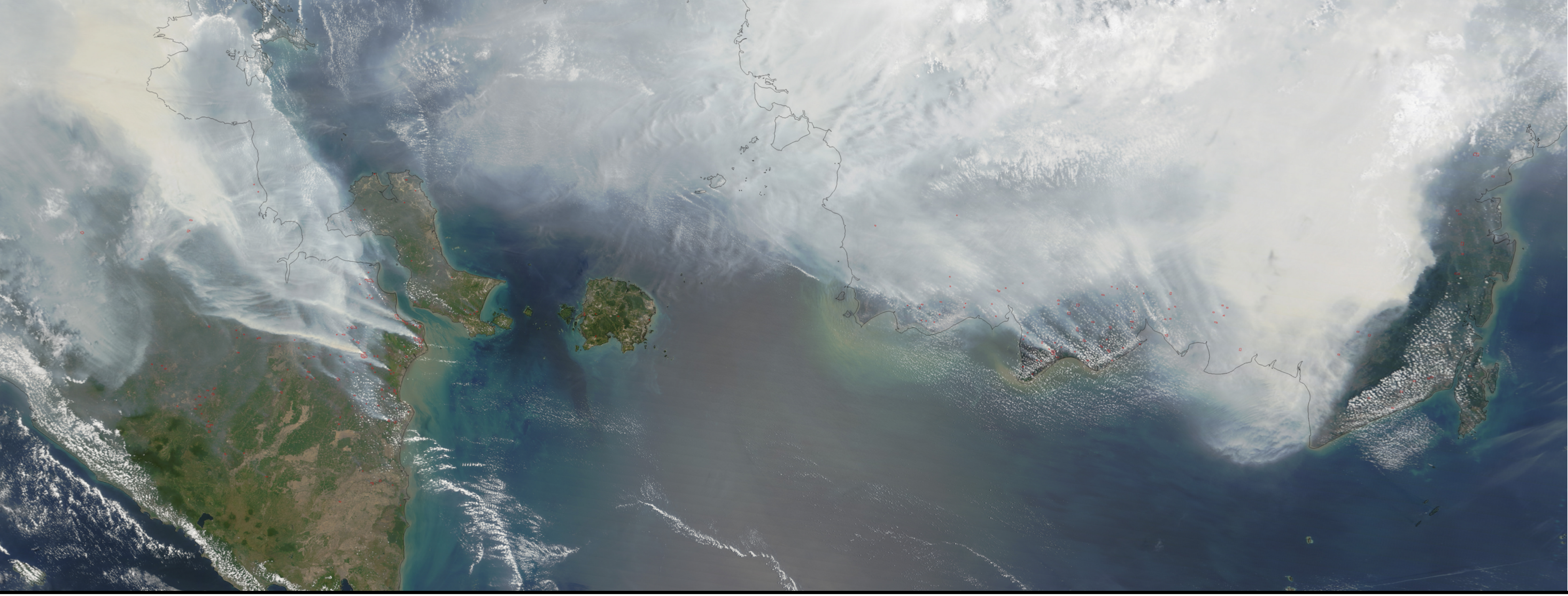


Important Information Regarding OMI

- Almost 50% data loss since 2008 (row anomaly effect)
- Affects all OMI products
- Global coverage in ~2 days



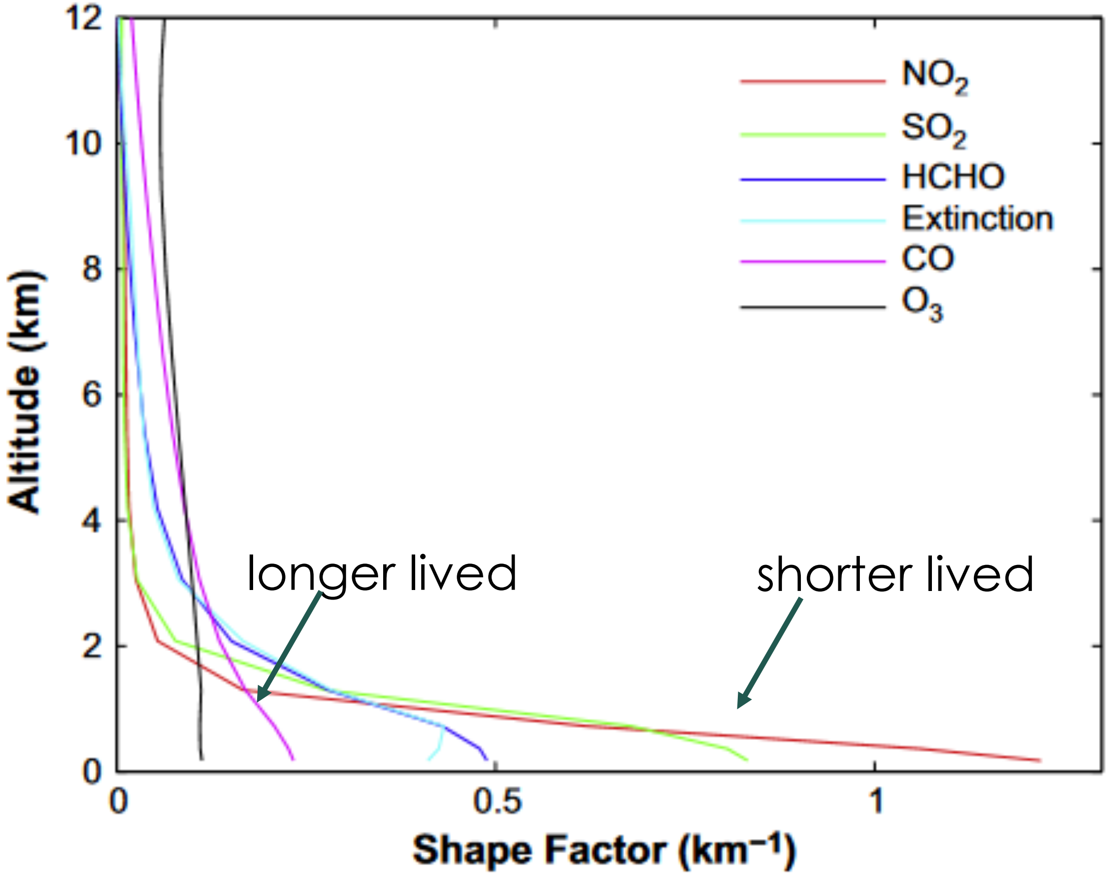




O_3

OMI Ozone in the Troposphere

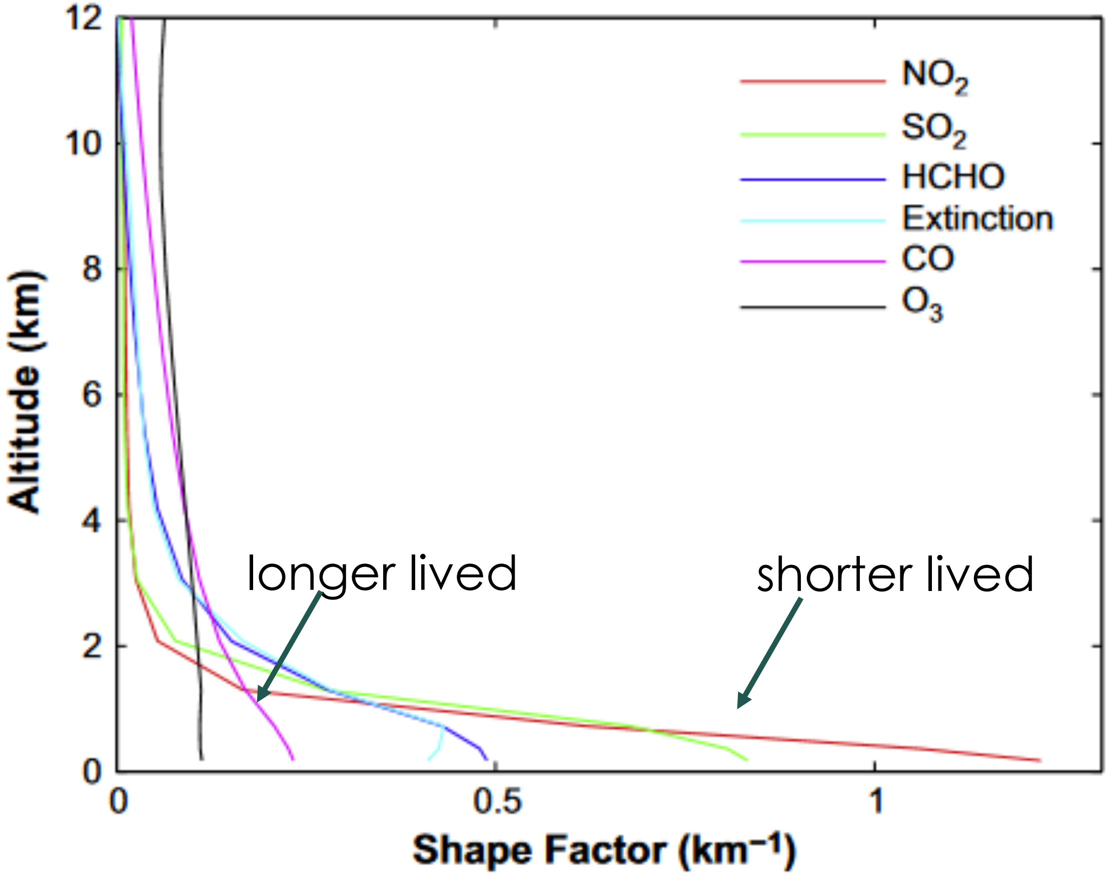
- Why measure tropospheric ozone?
  - Ozone is a tropospheric pollutant with negative health impacts for humans (e.g., aggravation of asthma and other lung diseases) as well as ecosystems (e.g., crop damage)
  - Ozone also plays an important role in the chemistry of the troposphere



Martin, R.V., Satellite remote sensing of surface air quality, Atmos. Environ., 42, 7823-7843, 2008.

OMI Ozone in the Troposphere

- OMI is not sensitive to ozone near the surface
- Tropospheric ozone products cannot be used for air quality monitoring
- Retrieval of boundary layer ozone from satellite remote sensing remains a daunting task
  - Separation of total column into stratospheric and tropospheric contributions
  - Potential for significant free tropospheric contribution to the tropospheric column



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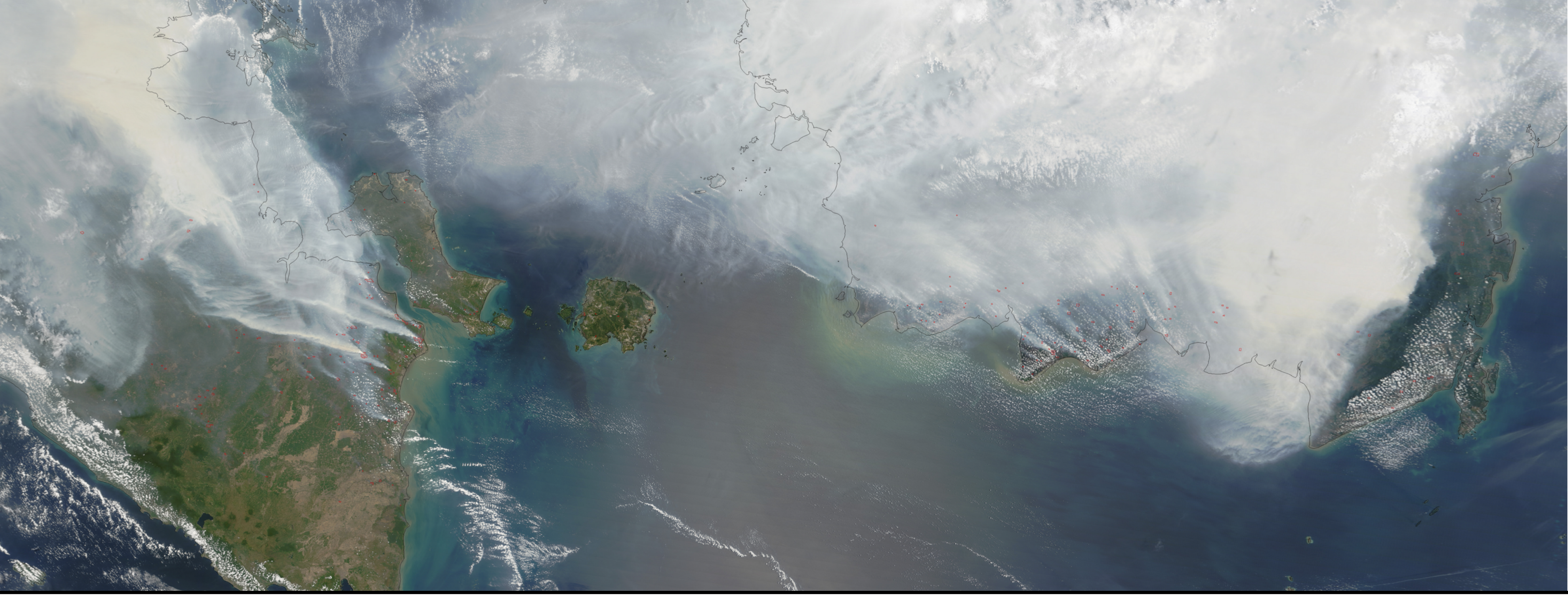
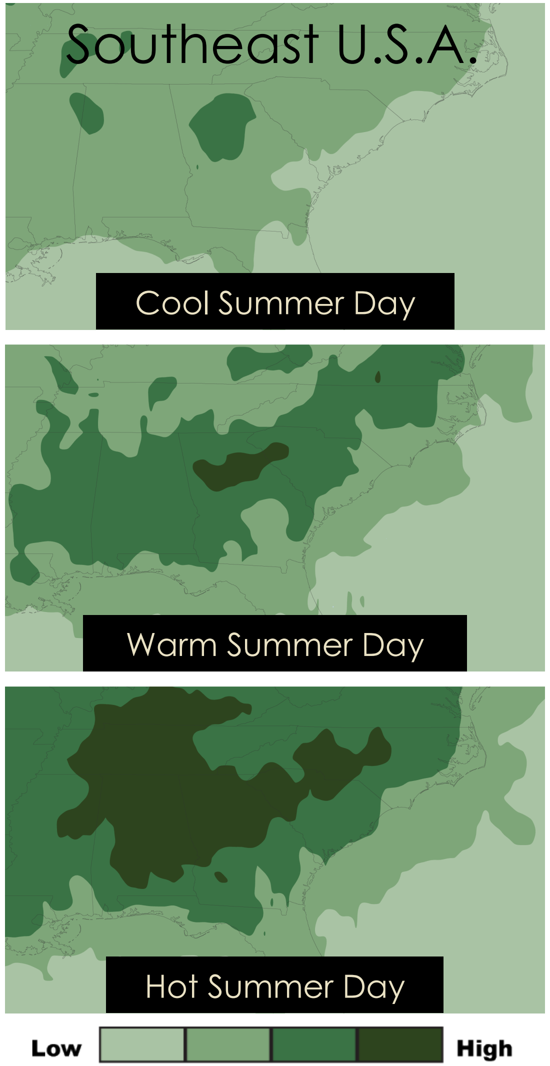


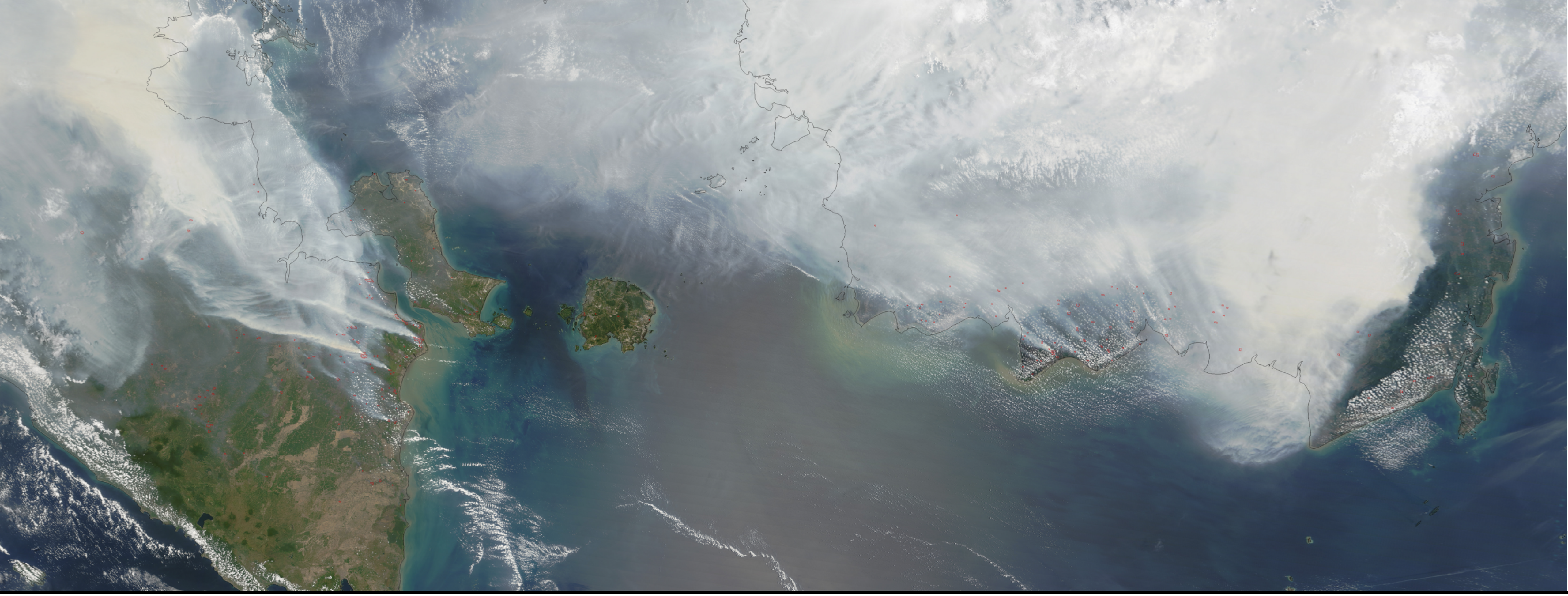
HCHO

OMI Formaldehyde (HCHO)

- Why measure formaldehyde?
  - it is an ozone precursor and can serve as a proxy for total VOC chemical reactivity and isoprene emissions
- Daily and monthly gridded data (0.25° x 0.25°) available from http://h2co.aeronomie.be/
- Level 2 gridded data for the NASA/Smithsonian retrieval can be found at https://disc.gsfc.nasa.gov/datasets/OMHCHOG_V003/summary
- Caution when using these data for quantitative analyses
  - When compared to observations, satellite observations of HCHO are biased low
  - Data have large uncertainties, so require spatial and/or temporal averaging to cancel random noise



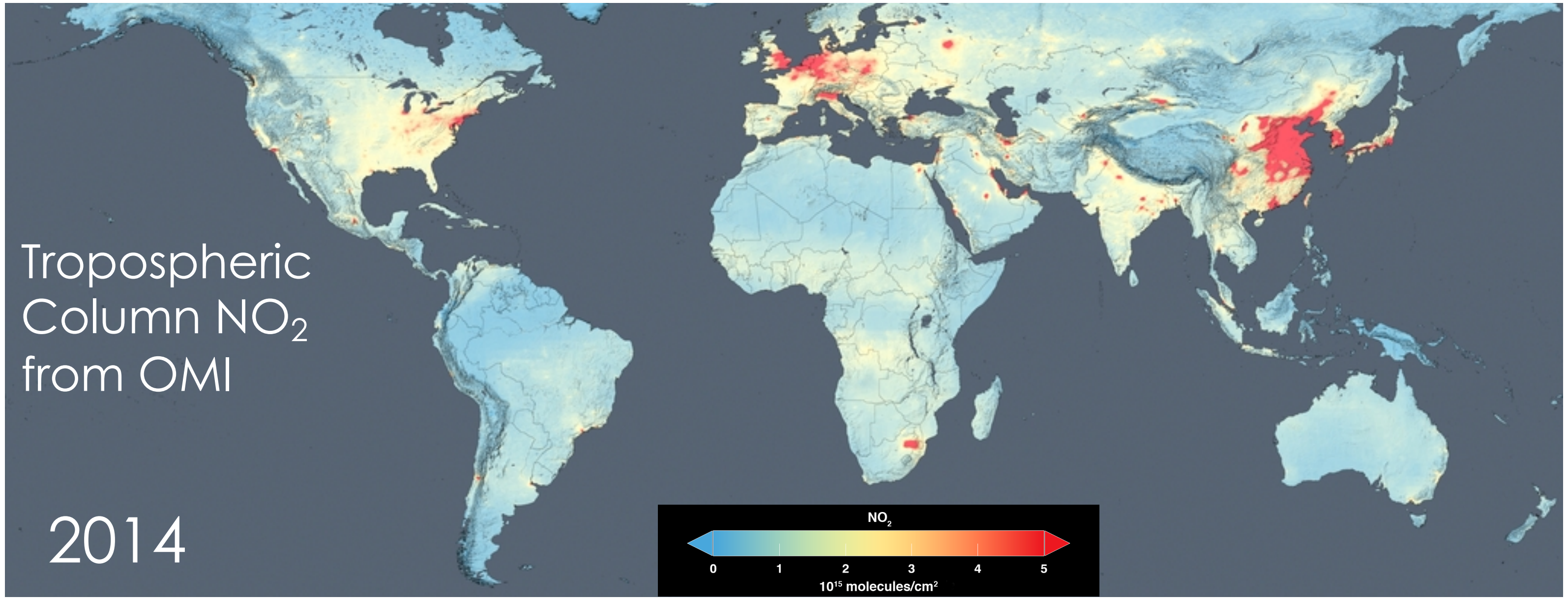
Source: Bryan Duncan (NASA)



Tropospheric Column NO_2

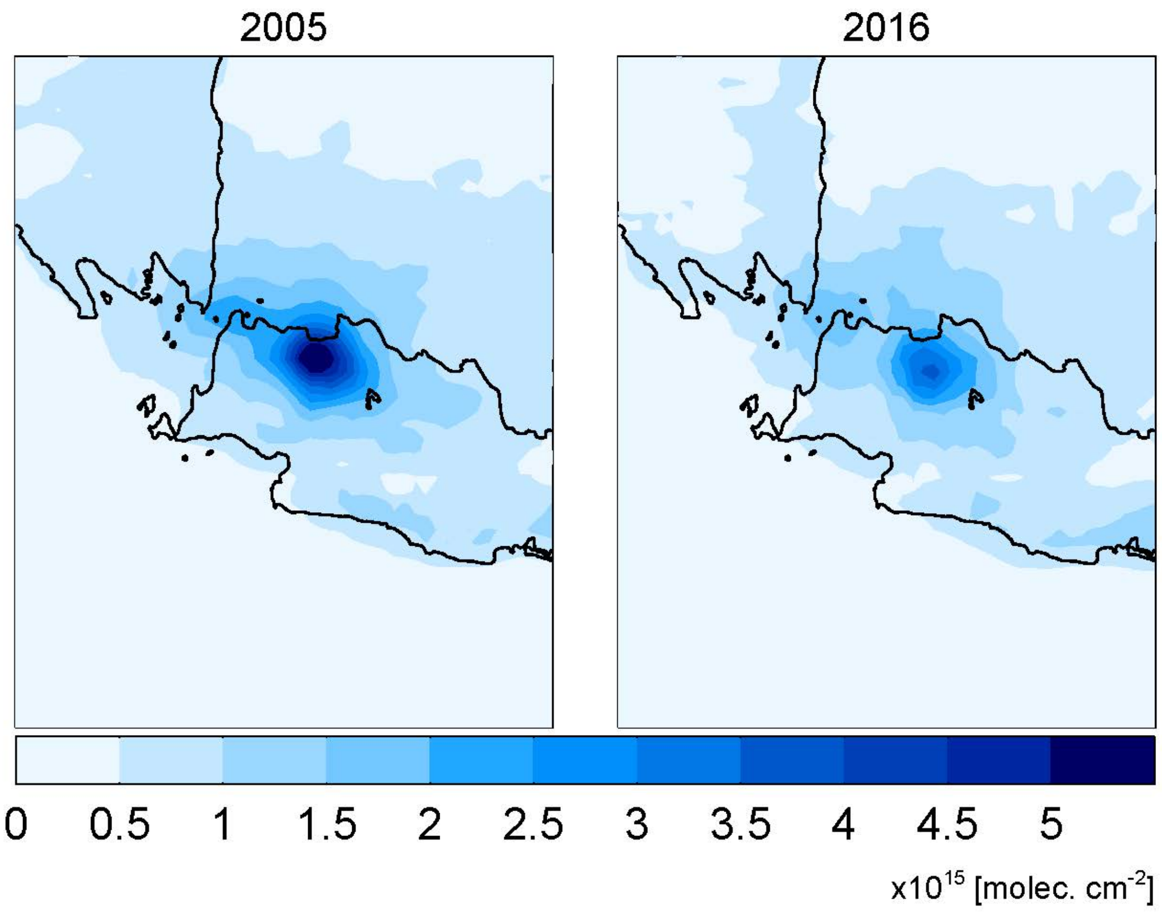
Nitrogen Dioxide (NO_2)

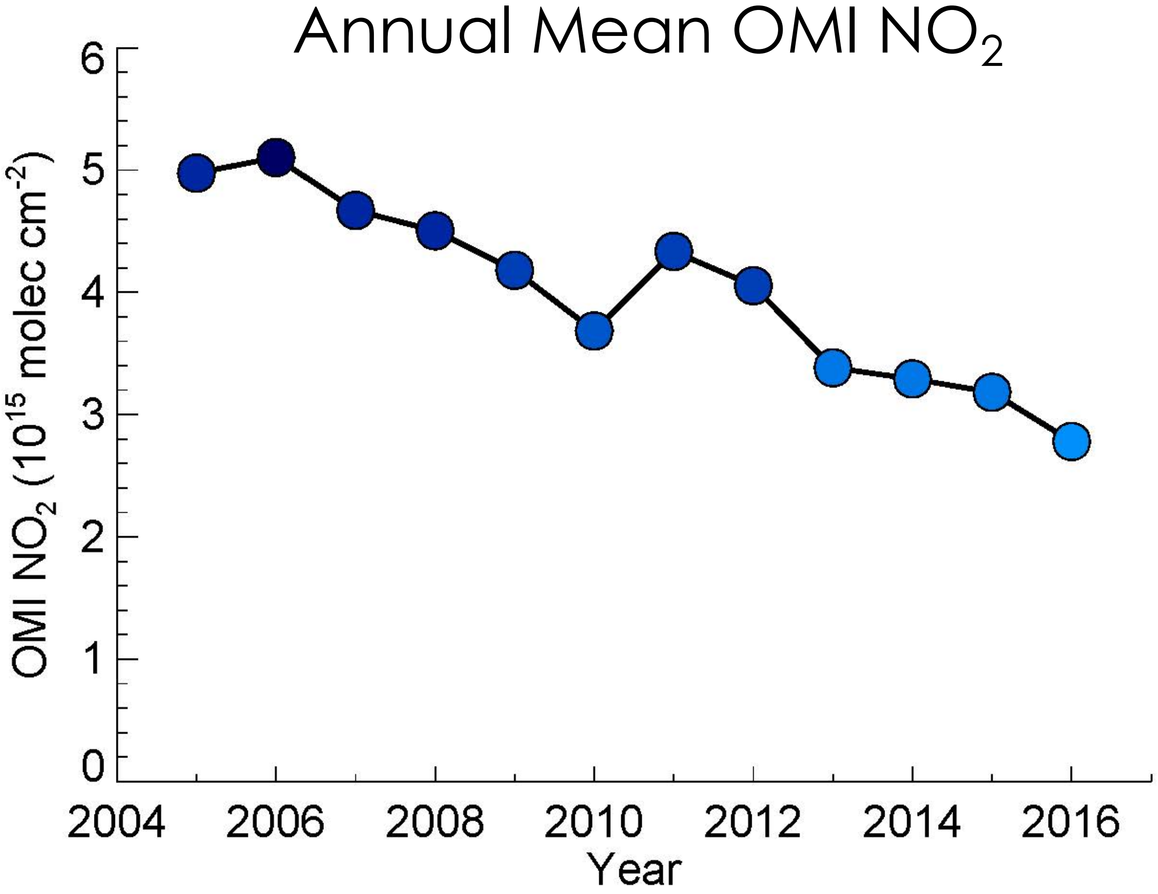
- Why measure NO_2?
  - NO_2 is an ozone precursor and health irritant
  - Sources: Fires, industrial and transportation sources, stationary sources (e.g. power plants), but emissions can vary depending on fuel type and conditions
  - High concentrations in the planetary boundary layer (PBL)



https://svs.gsfc.nasa.gov/4412

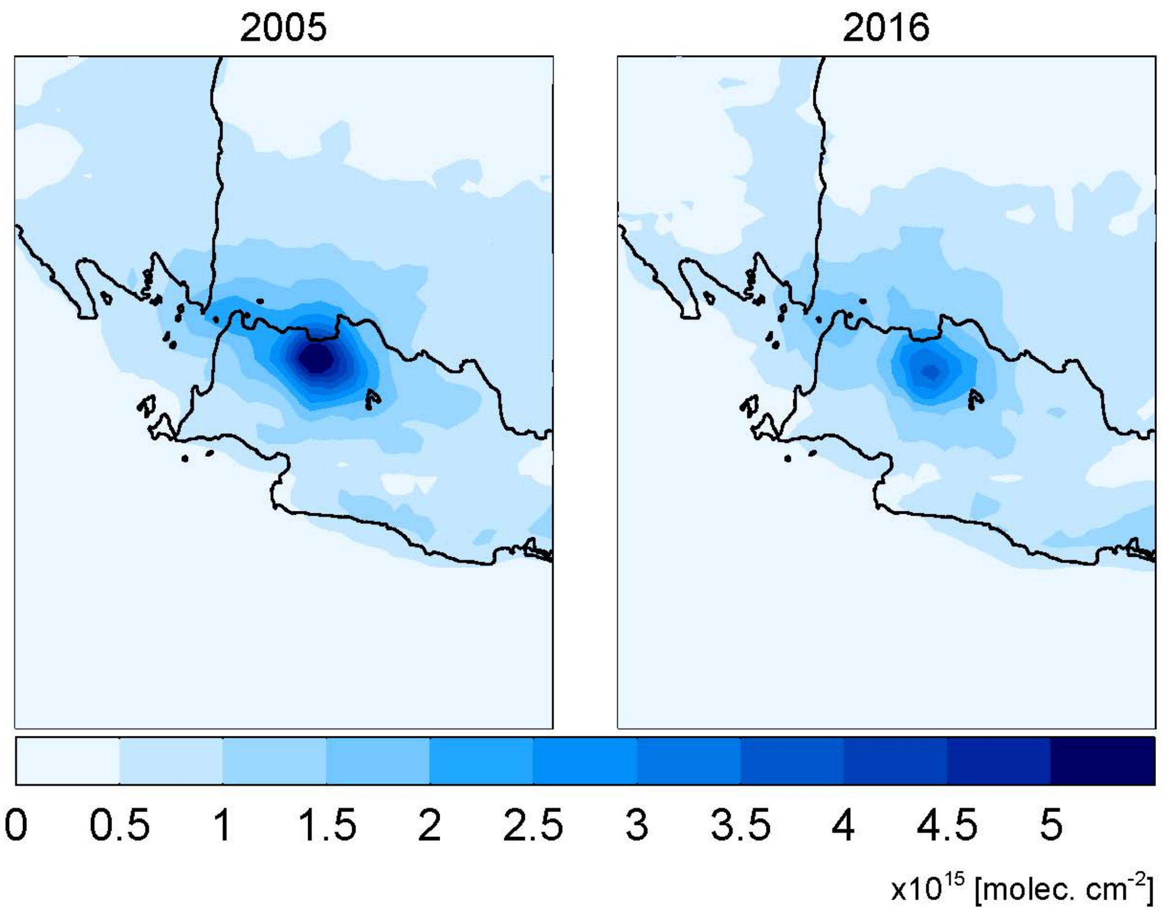
OMI NO_2 Shows That Levels in Jakarta Have Dropped by ~40%

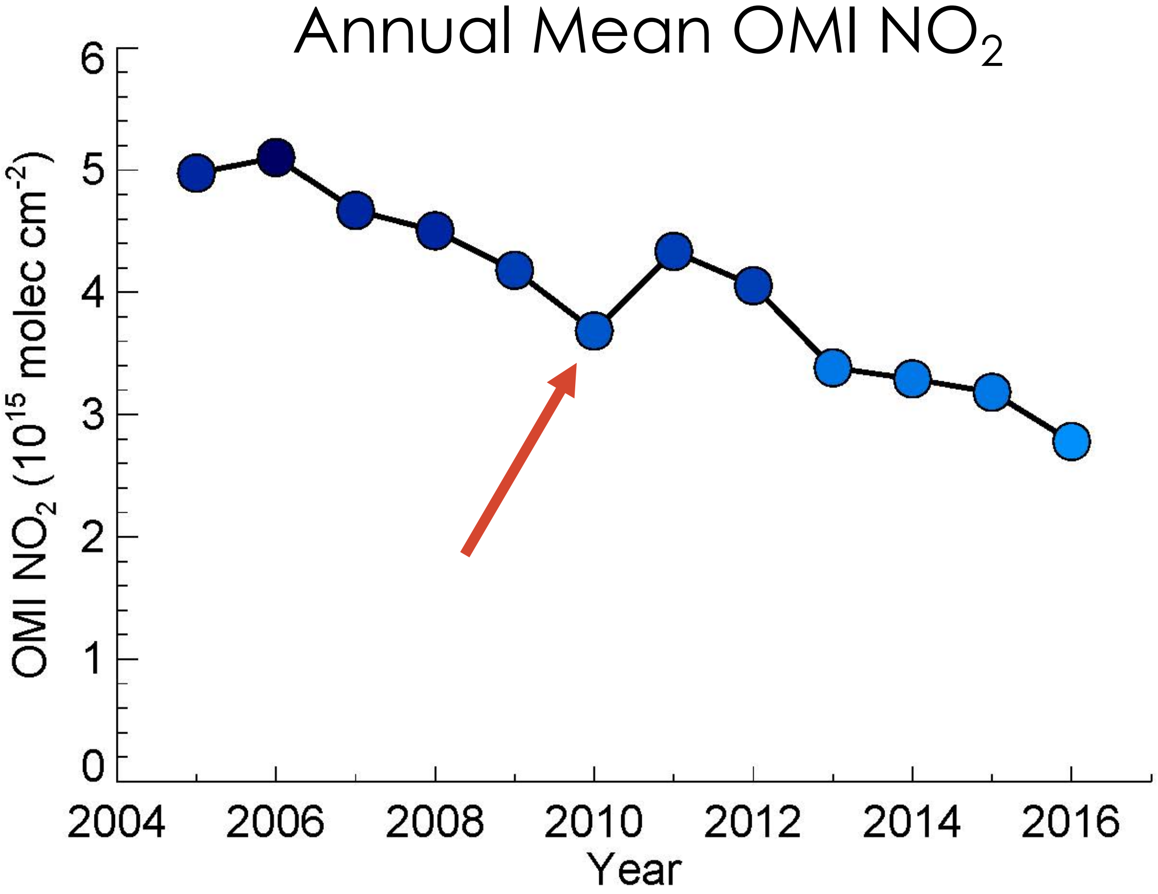




Melanie Follette-Cook

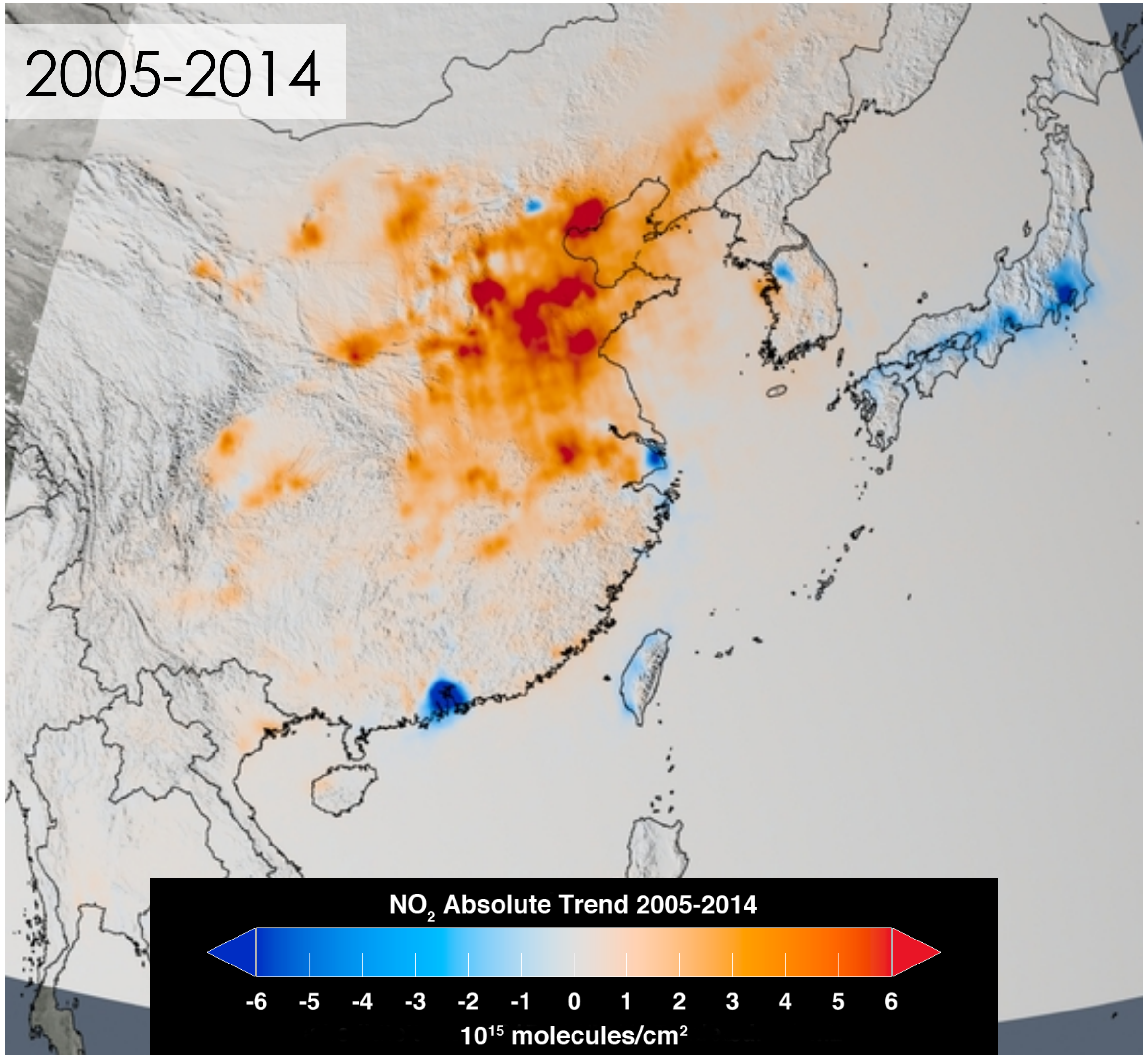
OMI NO_2 Shows That Levels in Jakarta Have Dropped by ~40%



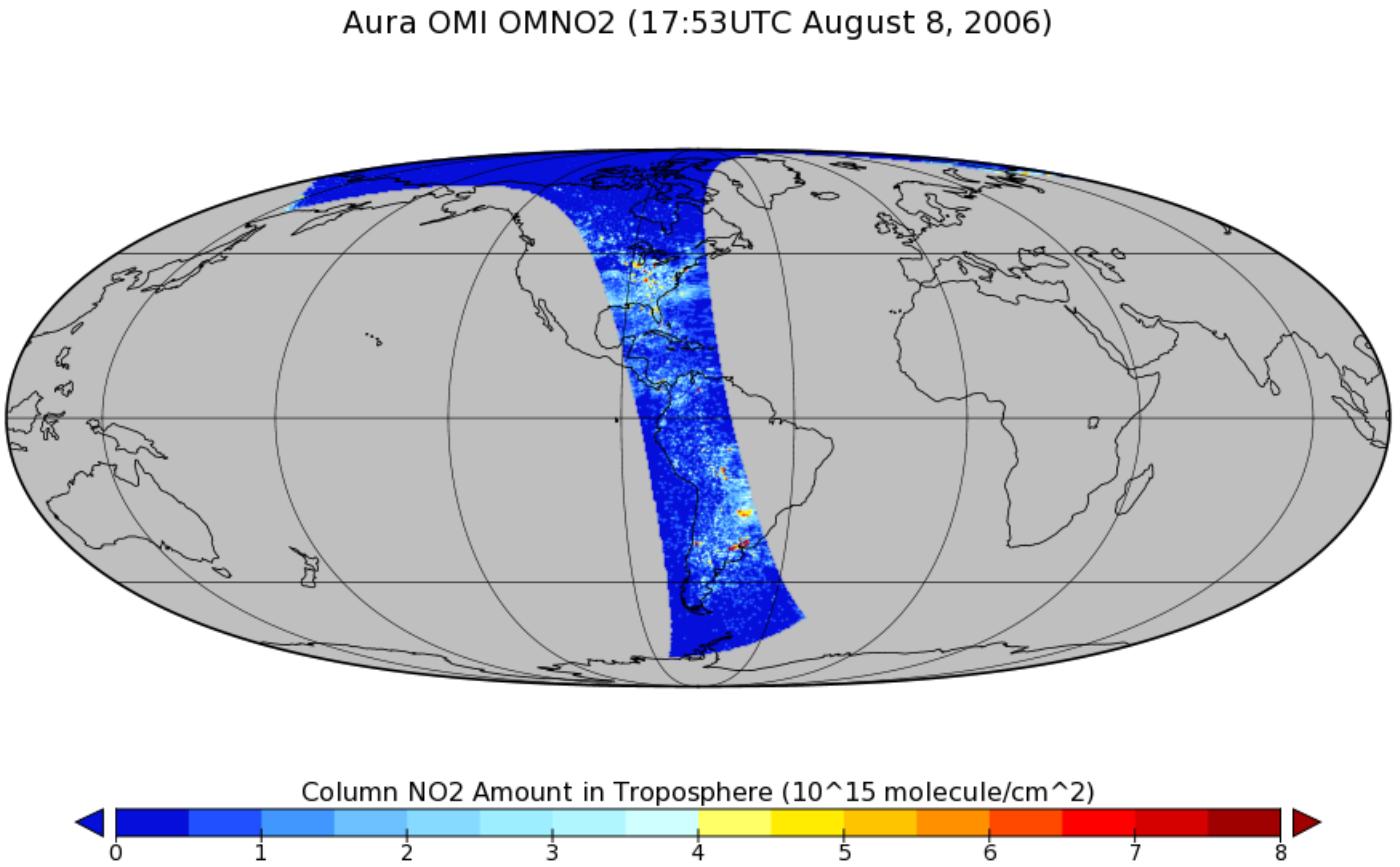


Melanie Follette-Cook

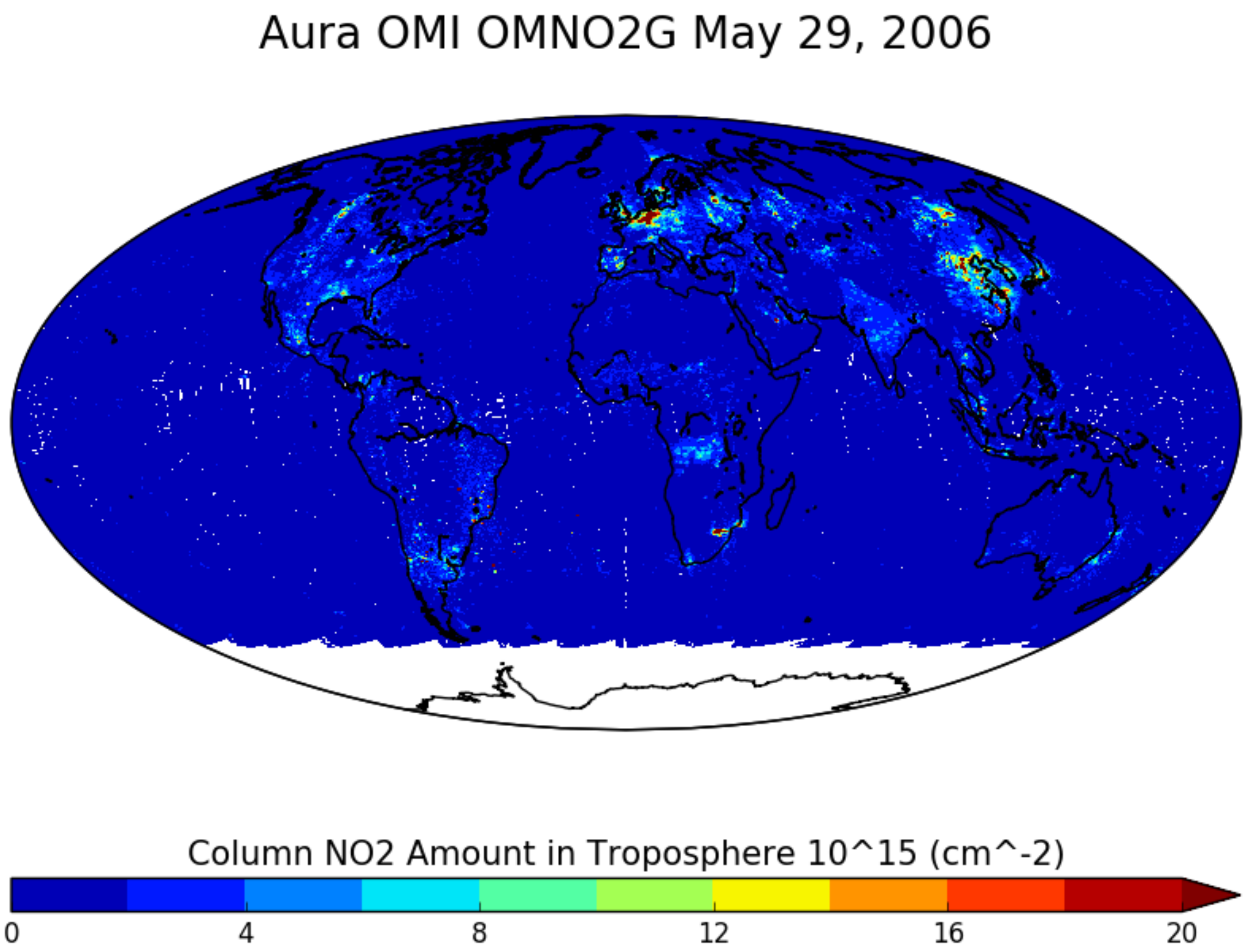
OMI Detects NO_2 Changes in Pollution Over Time



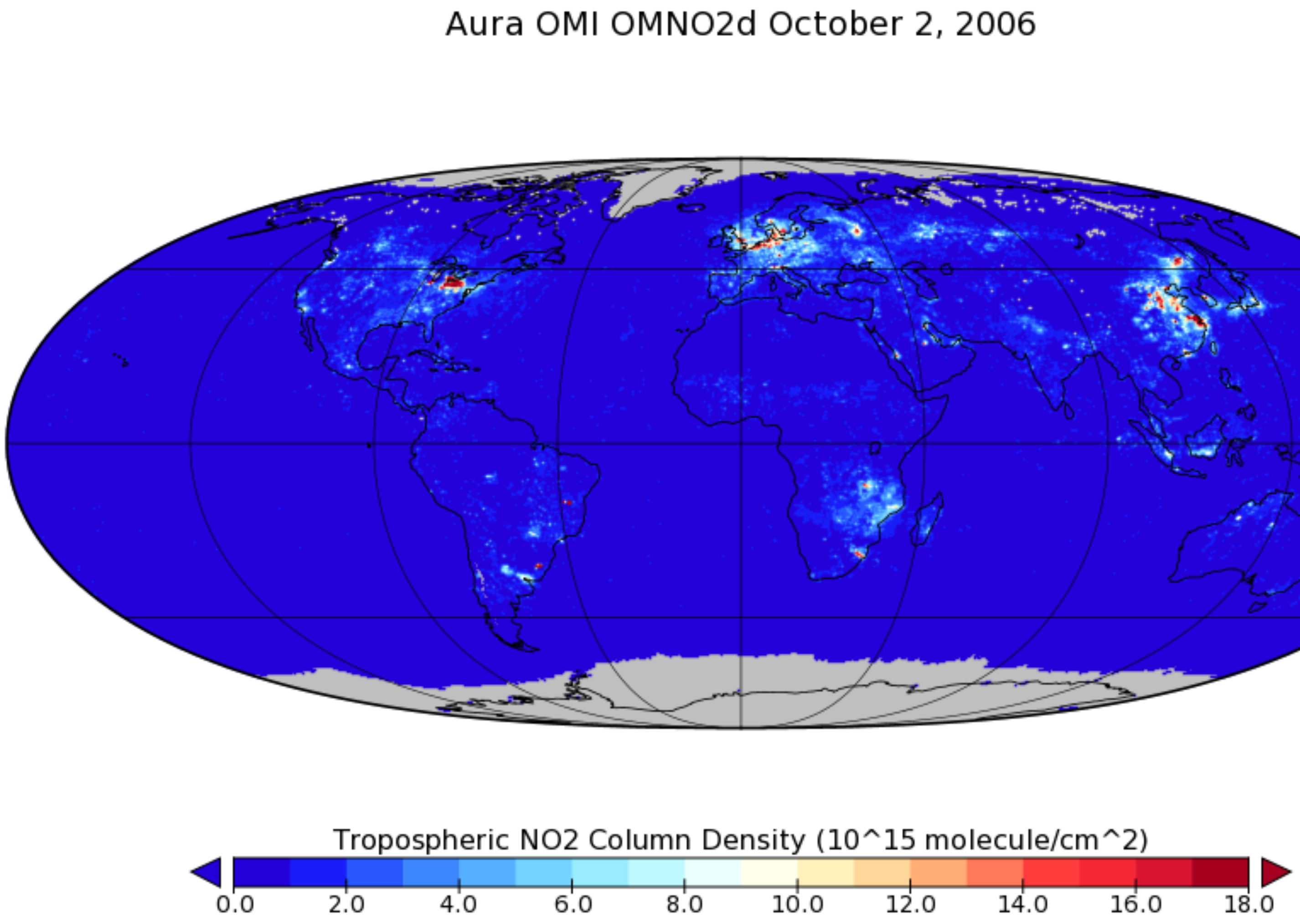
$OMNO_2$ Level 2 Product – Native Resolution



OMNO2g L2 Gridded Product (0.25° x 0.25°) – *no pixel averaging*



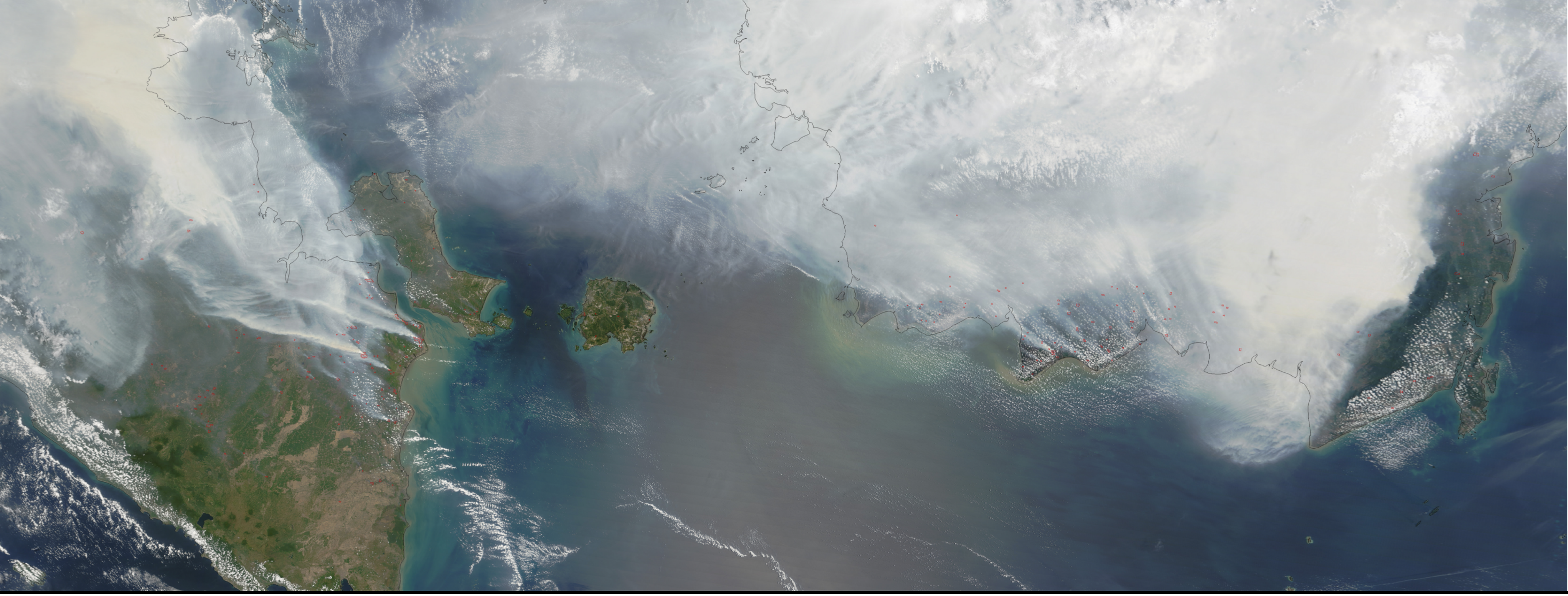
OMNO2d L3 Gridded Product (0.25° x 0.25°) – *pixel averaging*



OMI NO_2 Parameter information (OMNO2)

Name	Description	Unit	Notes
ColumnAmountNO2Trop	Tropospheric Column NO_2	Molec / cm^2	• Use row anomaly flag: Use only rows 4-54 (where the first row = 0) • Use only scenes with: radiative cloud fraction < 0.5 solar zenith angle < 85° terrain reflectivity < 0.3
TerrainReflectivity		Unitless	Scale factor: 0.001
CloudRadianceFraction		Unitless	Scale factor: 0.001
SolarZenithAngle		Deg	In geolocation fields

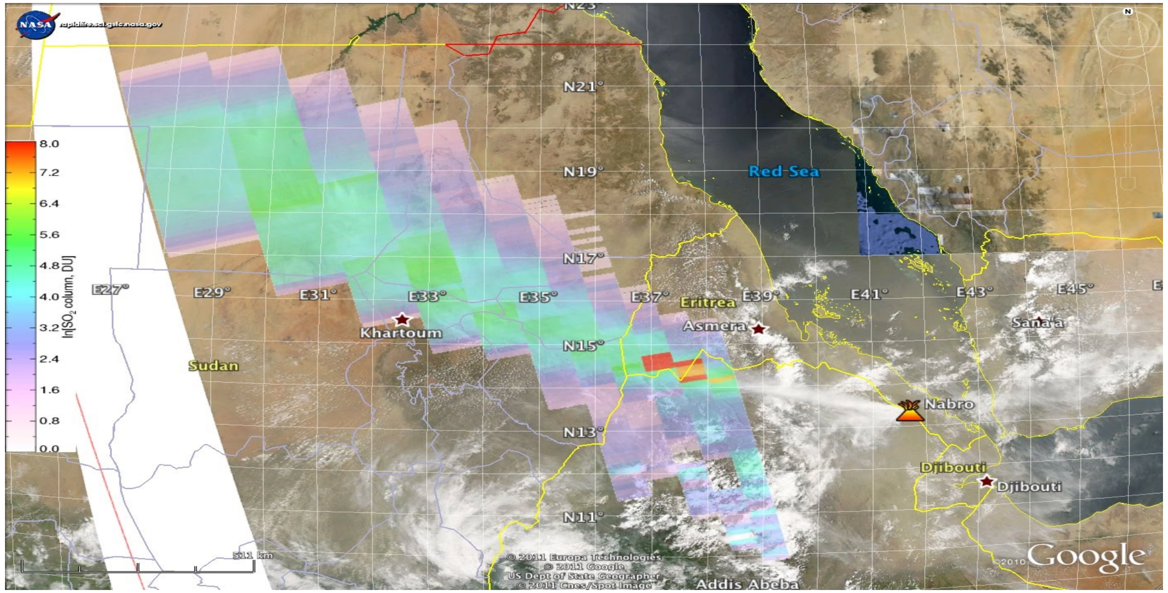
- All fill values are high negative numbers: $(-2.^{100} \approx -1.26765\times10^{30})$



Anthropogenic & Volcanic SO_2

OMI SO_2 in the Boundary Layer

- Why measure SO_2?
  - SO_2 has also been linked to adverse respiratory effects
  - Contributes to acid deposition
  - Sources: Volcanoes, coal and oil burning
- PBL Dataset Short Name = OMSO2e
  - Product Level: 3
  - Daily, beginning October 1, 2004
  - Resolution: 0.25° x 0.25°
  - File Size (approx): 5 mb

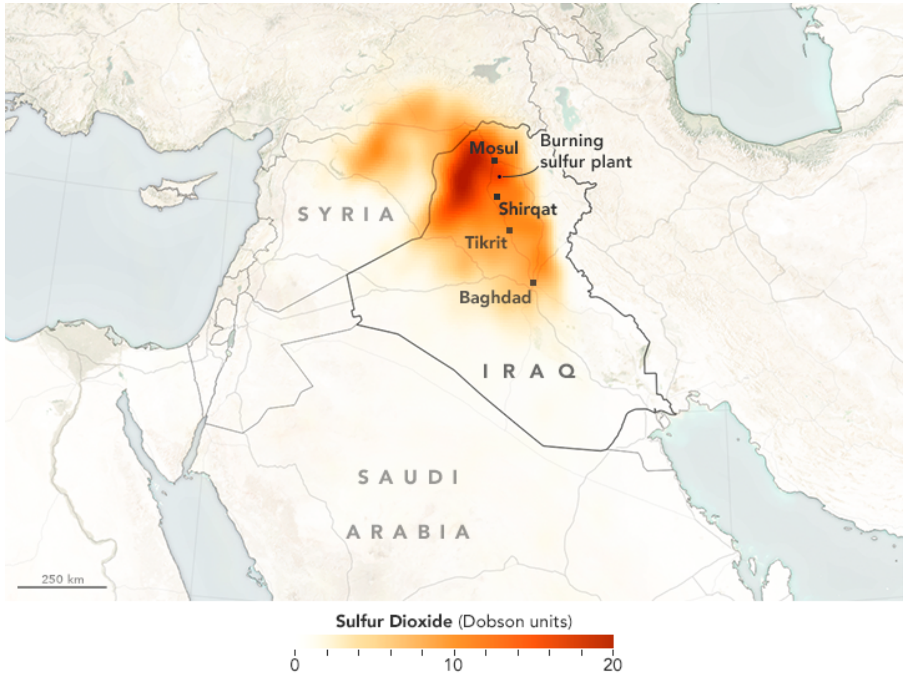


Aqua MODIS visible image of the Nabro (Eritrea) eruption on June 13, 2011 and the SO2 plume overlaid.

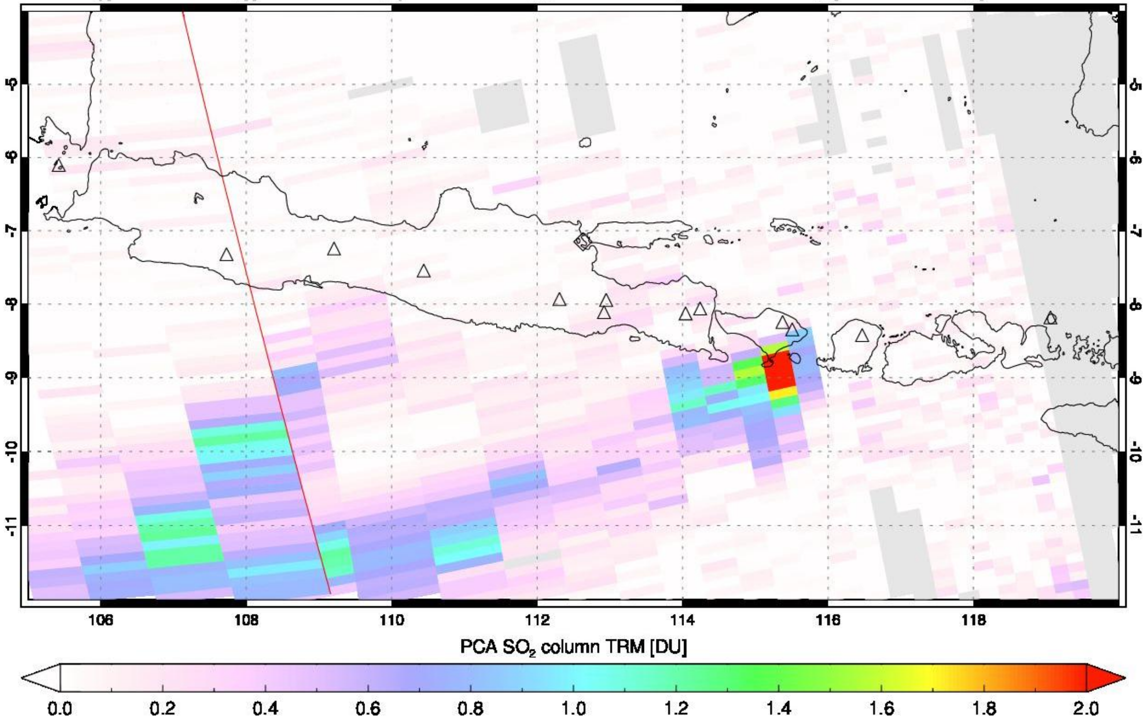
- Screened for data quality (e.g., OMI row anomaly, clouds, etc.)
- https://disc.sci.gsfc.nasa.gov/datasets/OMSO2e_V003/summary

Perspective: What is Considered High SO_2?

OMI SO_2 from Sulfur Mine Fire October 24, 2016



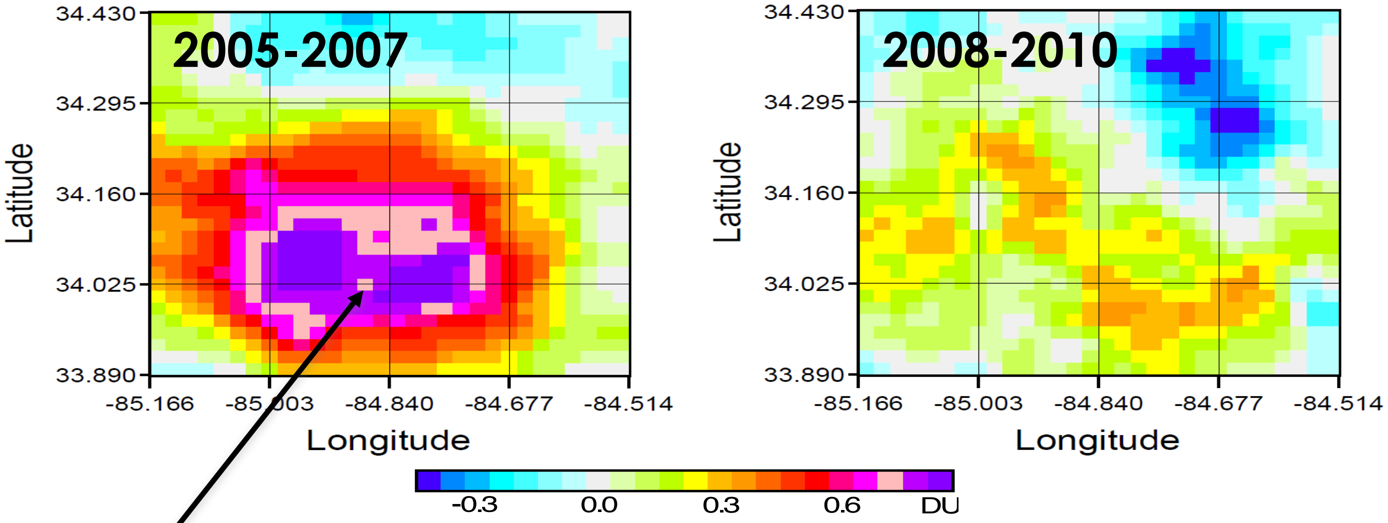
OMI SO_2 from Agung Volcano November 29, 2017

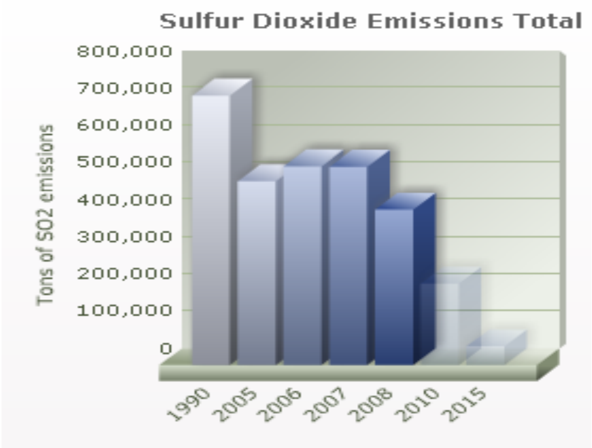


Left: https://earthobservatory.nasa.gov/IOTD/view.php?id=88994; Right: https://so2.gsfc.nasa.gov/

Perspective: What is Considered High SO_2?

#1 U.S. Source: Bowen Coal Power Plant, Georgia (3500 MW),
SO_2 Emissions: 170 kT in 2006





"In **2008**, the mammoth construction program yielded the first scrubbers, sophisticated equipment that will reduce our overall systems emissions by as much as 90 percent"

Georgia Power website

Source: V. Fioletov, et al., 201

OMI SO_2 Level-2 Product Summary (OMSO2)

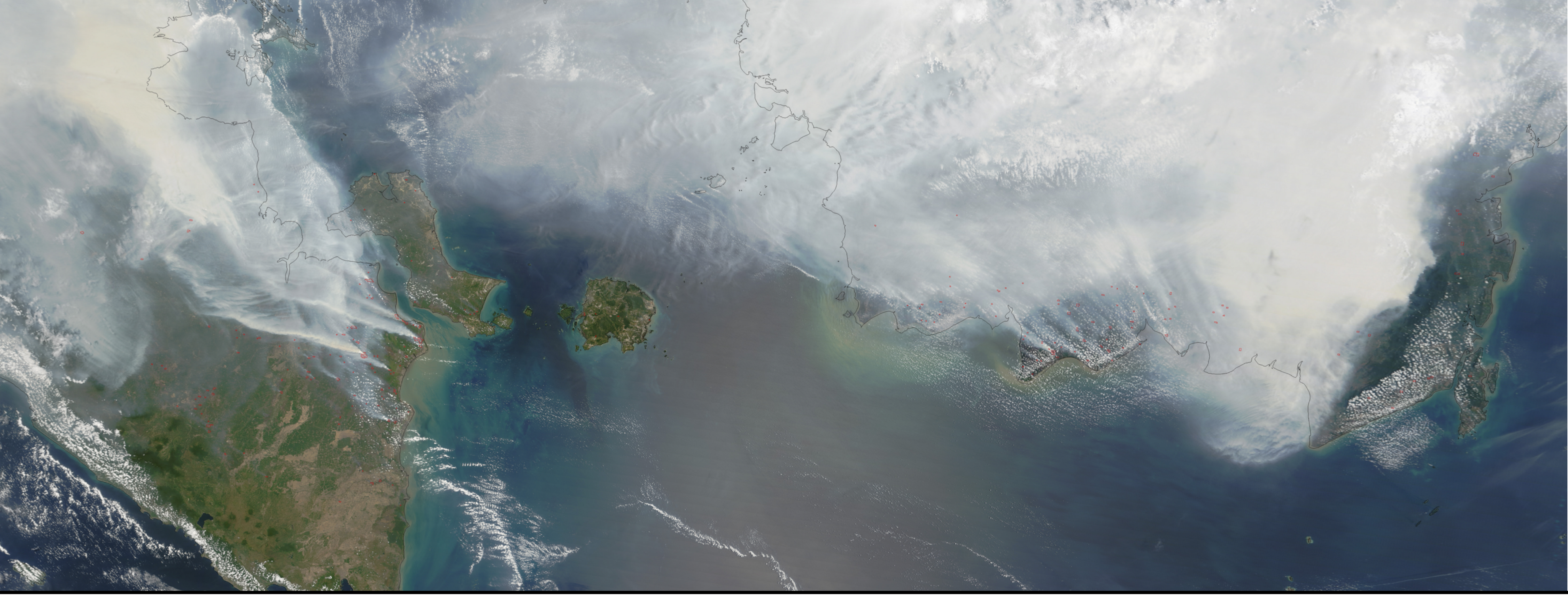
SO_2 Product	SDS Name	Estimated center of plume	Use
PBL SO_2	ColumnAmountSO2_PBL	0.9 km	Near-surface pollution
TRL SO_2	ColumnAmountSO2_TRL	3 km	Volcanic degassing
TRM SO_2	ColumnAmountSO2_TRM	8 km	Plumes from moderate eruptions, and long range pollution transport
STL SO_2	ColumnAmountSO2_STL	18 km	Explosive volcanic eruptions

Note: Each retrieval listed here yields total column values, and represents a different assumption of SO_2 plume height. These should therefore not be added together.

OMI SO_2 Parameter (SDS) information (OMSO2)

SDS name	Description	Unit	Notes
ColumnAmountSO2_PBL	Total Column SO_2	DU	• use only rows 4-54 (where the first row = 0) • use only scenes with radiative cloud fraction < 0.3 solar zenith angle < 70°
ColumnAmountSO2_TRL /TRM/STL	Total Column SO_2	DU	• All rows can be used • Use only scenes with solar zenith angle < 70°
RadiativeCloudFraction		Unitless	No scale factor
SolarZenithAngle		Deg	In geolocation fields

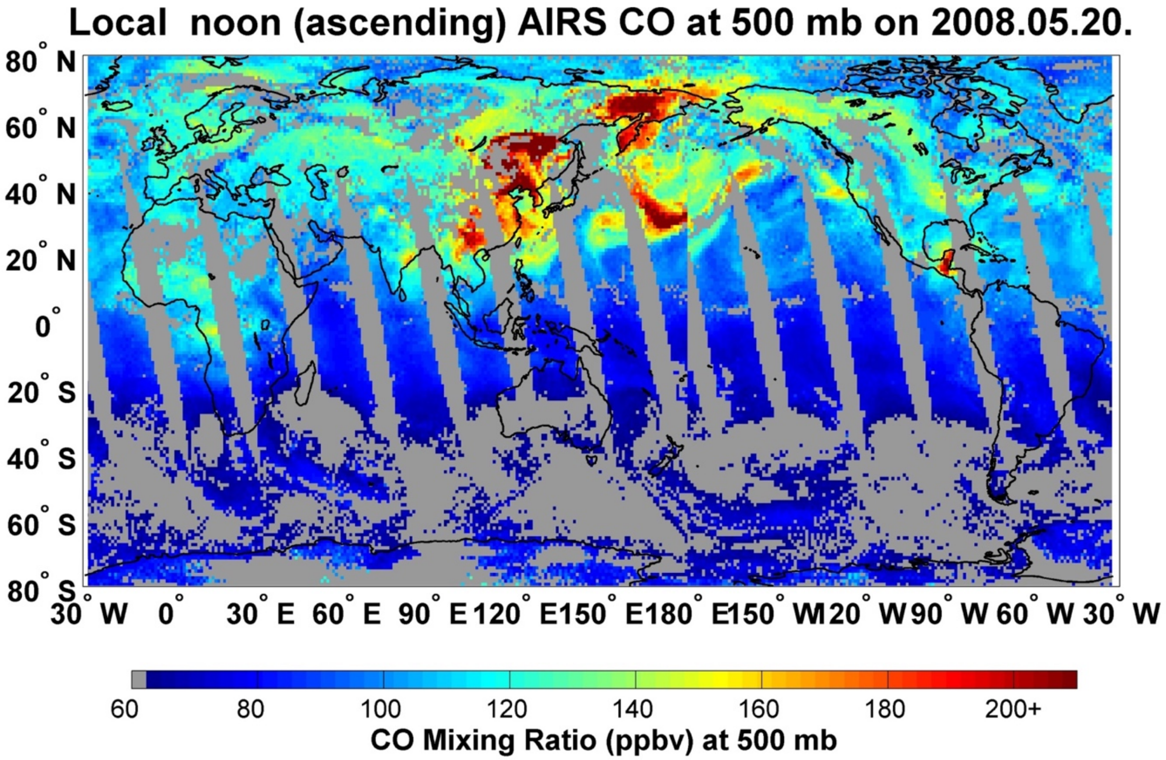
- As of the latest version (v1.3), the OMSO2 documentation does not recommend using the included data quality flags for screening
- All fill values are high negative numbers: $(-2.^{100} \approx -1.26765\times10^{30})$



Carbon Monoxide (CO)

Carbon Monoxide

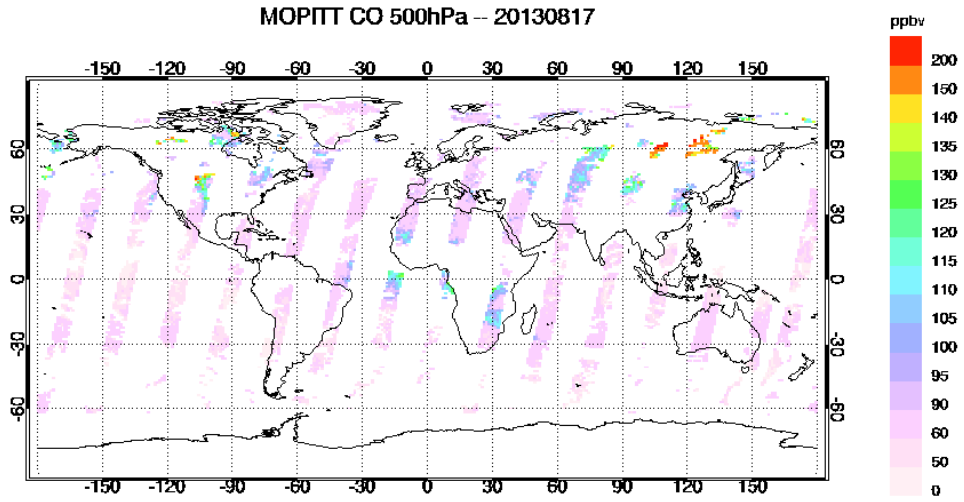
- Why measure CO?
  - Major global precursor for O_3, and dominant sink for OH
  - Relatively long lifetime (~1-2 months) makes it a useful tracer of transport
- Typically measured as a column density
- Instruments (e.g. MOPITT, AIRS) tend to have good sensitivity to CO in the mid-troposphere (~500 mb)
- Current sensors: AIRS, MOPITT, IASI



Measurements of Pollution in The Troposphere (MOPITT)

https://www2.acom.ucar.edu/mopitt

- Operational since 2000
- Global coverage every 3 days
- Nadir, Pixel size
  - 22 km^2 at nadir
- Swath Width: 640 km
- Equator Crossing Times
  - 10:30 (descending)
- Three retrievals
  - TIR: Highest temporal stability
  - NIR: daytime, column only
  - TIR/NIR (Joint): Greatest sensitivity to lower troposphere, but larger errors



- Profile Measurements:
  - 10 pressure levels including the surface (surface – 100 hPa)
- Data source:
  - Level 2 pixel
  - Level 3 gridded 1° x 1° resolution

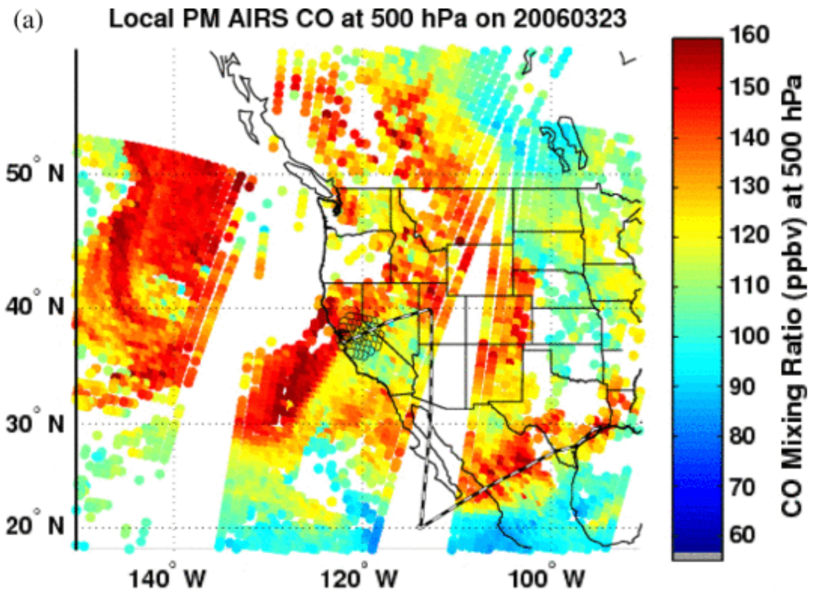
Image Source: NCAR UCAR

Atmospheric Infrared Sounder (AIRS)

http://airs.jpl.nasa.gov/

- Operational since Sep 2002
- Daily coverage
- Nadir, Pixel size:
  - 14 km at nadir
  - 41x21 km edges
- Swath Width: 1,650 km
- Equator Crossing Times
  - 13:30 (ascending)
  - 1:30 (descending)

- Profile Measurements:
  - 9 vertical layers
  - 901.866 hPa – 0.16 hPa
- Data:
  - Level 2 pixel
  - Level 3 gridded 1° x 1° resolution

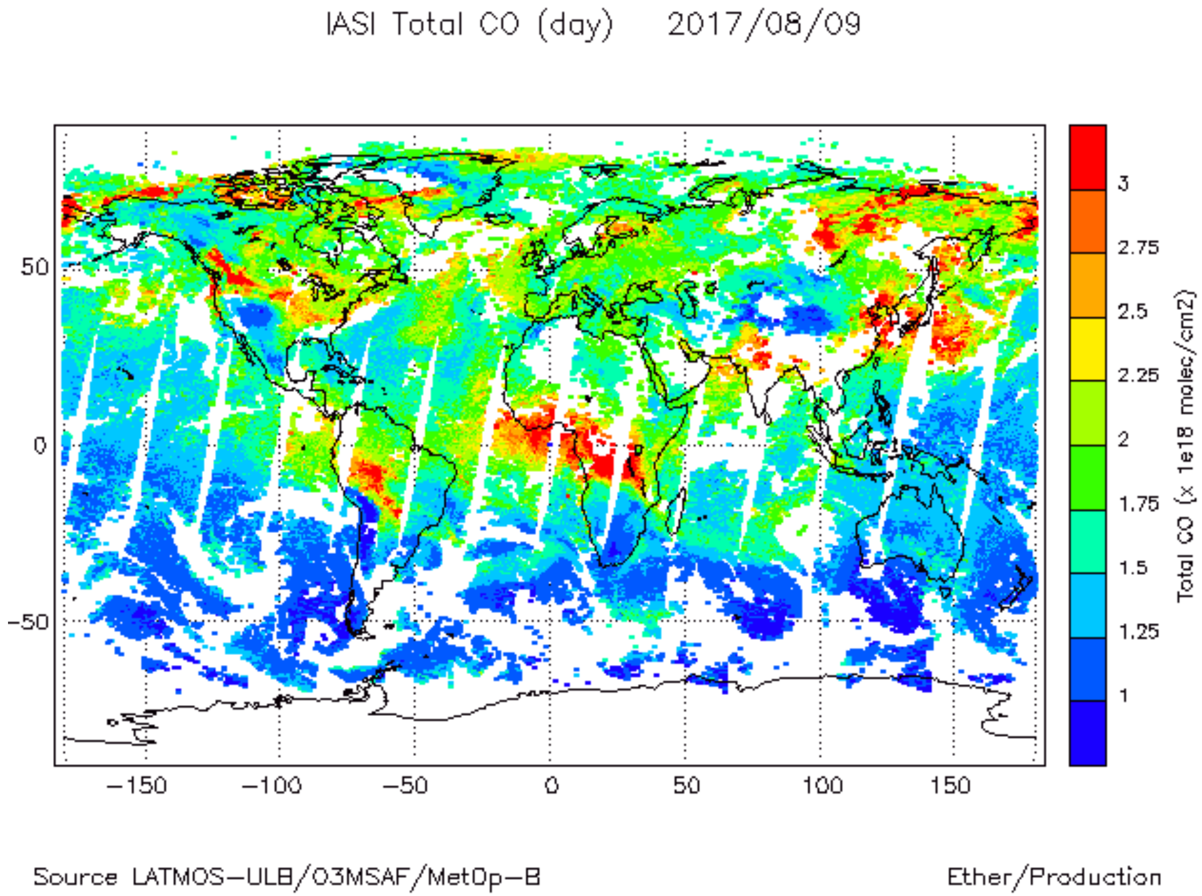


Source: Figure 6a from McMillan et al. (2011)

Infrared Atmospheric Sounding Interferometer (IASI)

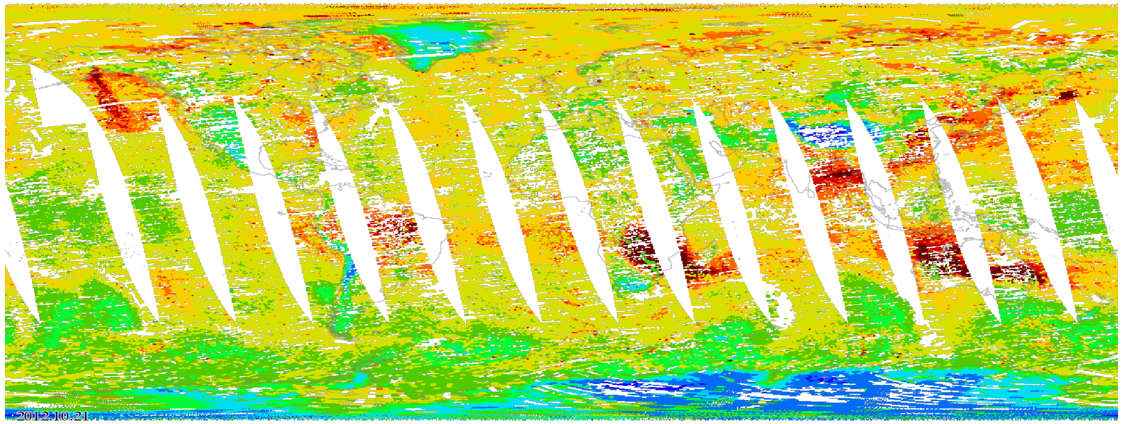
http://bit.ly/ESA-IASI

- Operational since 2006
- Daily coverage
- Nadir, Pixel size
  - 12 km^2 at nadir
- Swath Width: 2200 km
- Equator Crossing Times
  - 9:30 (descending)
  - 21:30 (ascending)
- CO Columns available in NRT
  - Within three hours of observation
- 18 layers

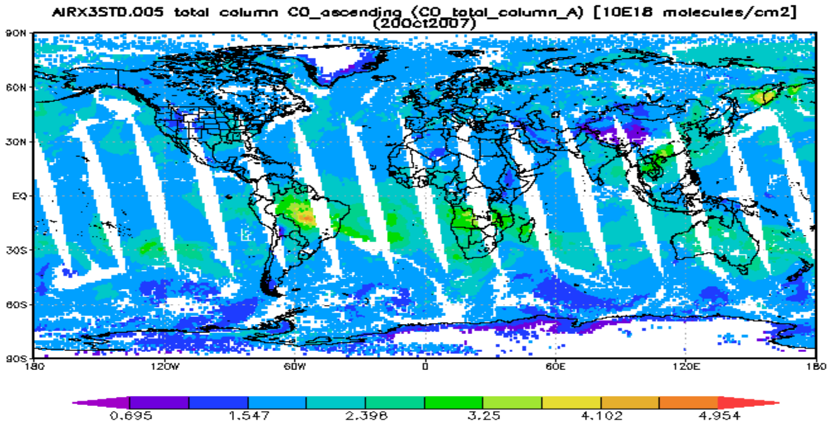


AIRS vs. MOPPITT CO – Daily Coverage

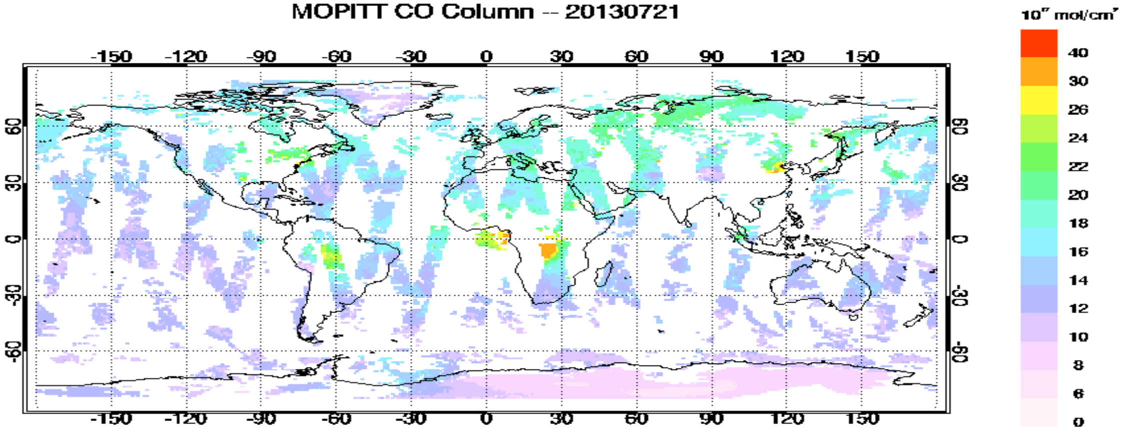
AIRS Level 2 from NRT Website



AIRS Level 3, 1°x1° from Giovanni



MOPPITT Level 3, 1°x1°



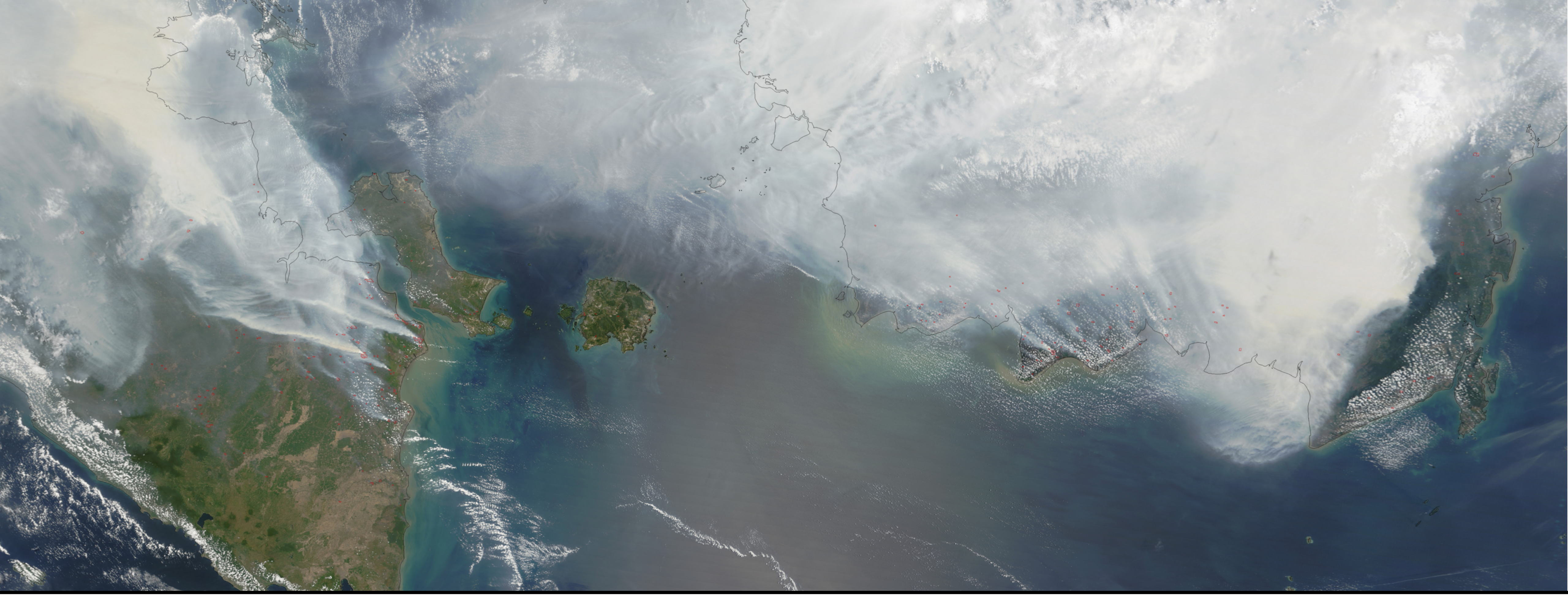
Comparison Chart - CO

	MOPITT	TROPOMI	AIRS	IASI
Product / Pixel size	22 x 22 km^2	7 x 7 km^2	14 x 14 km^2	12 x 12 km^2
Swath Width	650 km	2600 km	1,650 km	2,200 km
Global Coverage	3 days	daily	2x per day	2x per day
Overpass Time (local time)	10:30	13:30	13:30	9:30, 21:30
Product Resolution	L3: 1° Grid	Data should be released in 2018	L3: 1° Grid	NO L3 Product
Products Available	L2 L3, Daily, Monthly	Data should be released in 2018	L2 granule L3	L2 NOAA & ESA
Vertical Sensitivity	Column: mid & lower troposphere	Column: mid & lower troposphere	mid troposphere	mid tropo-sphere

Questions and Discussion

- Name a difference between retrievals of trace gases and retrievals of aerosols.

- What is the difference between a Dobson unit and ppmv?



Questions